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Phosphate Rock Availability—World

A Minerals Availability Program Appraisal

By R. J. Fantel, T. F. Anstett, G. R. Peterson, K. E. Porter, and D. E. Sullivan

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PREFACE

The Bureau of Mines Minerals Availability Program is assessing the worldwide availability of nonfuel minerals. The program identifies, collects, compiles, and evaluates information on active and developing mines, explored deposits, and mineral processing plants worldwide. Objectives are to classify domestic and foreign resources; to identify by cost evaluation, resources that are reserves; and to prepare analyses of mineral availabilities.

This report is part of a continuing series of Division of Minerals Availability reports to analyze the availability of minerals from domestic and foreign sources and those factors affecting availability. Analyses of other minerals are in progress. Questions about the Minerals Availability Program should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E St., NW., Washington, DC 20241.

CONTENTS

CONTENTS--Continued

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

in	inch	m	meter
km	kilometer	m^3	cubic meter
km^2	square kilometer	wt %	weight percent

PHOSPHATE ROCK AVAILABILITY—WORLD

A Minerals Availability Program Appraisal

By R. J. Fantel,[1] T. F. Anstett,[1] G. R. Peterson,[2]
K. E. Porter,[3] and D. E. Sullivan[4]

ABSTRACT

The Bureau of Mines investigated the resource potential of 201 mines and deposits in 28 market economy countries and 17 mines and deposits in the U.S.S.R. and China. The 201 mines and deposits evaluated from market economy countries contain an estimated 34.2 billion metric tons of recoverable phosphate rock (at the demonstrated resource level), with Morocco and Western Sahara accounting for 61% (21 billion tons), followed by the United States with 19% (6.4 billion tons). The 17 mines and deposits evaluated in the U.S.S.R. and China contain approximately 1.5 billion tons of potentially recoverable phosphate rock.

Potential annual capacity from low-cost, high-grade producing mines in the United States is estimated to decline significantly during the latter half of the next decade, and the United States will have to develop new, higher cost, lower grade mines in order to satisfy demand into the next century. Of the world's new production capacity which could likely be developed over the next decade, slightly over one-third could be produced at an estimated 1981 cost of $40 per ton or less, and about two-thirds would cost in the $40 to $50 range (including a 15% rate of return). In comparison, most of the competing phosphate rock from producing mines in Morocco could be produced for under $40 per ton.

The United States has sufficient demonstrated resources of phosphate rock (plus huge quantities at the identified and hypothetical resource levels) to satisfy domestic consumption for many years to come, but its future ability to compete in the major export markets against low-cost competitors is much more uncertain.

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INTRODUCTION

Phosphate rock, the only significant commercial source of the element phosphorus, is of vital importance to an expanding agricultural sector worldwide. Phosphorus, nitrogen, and potassium are the three primary nutrients necessary for plant growth. When these elements are either lacking or depleted from the soil, their addition is necessary to reestablish high agricultural yields. The growth of world agricultural production partially depends on the availability of phosphate fertilizers.

Phosphate rock consists of the calcium phosphate mineral apatite, with quartz, calcite, dolomite, clay, and iron oxide as the gangue constituents. Following industry practice, the term "phosphate rock" is defined in this paper as the beneficiated product of phosphate ore rather than the in situ material. After beneficiation, phosphate rock ranges from 26% to about 34% P_2O_5 (phosphorus pentoxide). Phosphate rock can be converted to phosphoric acid by the wet process, converted to elemental phosphorus in an electric furnace, or applied directly to acidic soils as direct-application fertilizer. The acceptability of phosphate rock for wet-process acid production is affected by the amounts of aluminum, iron, magnesium, and chloride in the concentrates. Phosphate rock containing more than 1% magnesium oxide (MgO), more than 3.5% iron oxide plus aluminum oxide, or more than 0.2% chlorine can cause problems in the manufacture of wet-process phosphoric acid.

Most of the phosphate rock produced in the world is used to manufacture wet-process phosphoric acid. Phosphoric acid is produced by digesting the apatite mineral, i.e., phosphate rock, in sulfuric acid. Diammonium phosphate (DAP), a common bulk blending-grade fertilizer chemical, is produced by reacting phosphoric acid with ammonia. If the phosphate rock is reacted with phosphoric acid, triple superphosphate (TSP) is produced. When wet-process phosphoric acid is subjected to evaporation, a higher concentration of phosphoric acid is produced, which when reacted with ammonia produces a liquid ammonium phosphate fertilizer (1).[5]

Phosphate animal feed supplements are produced by the defluorinization of either phosphate rock or phosphoric acid. Lime is reacted with defluorinated phosphoric acid to produce dicalcium phosphate. Phosphate rock at proper conditions and compaction is defluorinated in kilns at high temperature. These phosphate animal feeds are necessary supplements to assure nutritional quality of livestock diets (1).

Elemental phosphorus is produced by reducing phosphoric rock in electric furnaces and is marketed as is, or oxidized to produce anhydrous derivations and phosphoric acid. Phosphoric acid produced from elemental phosphorus is commonly used to manufacture sodium tripolyphosphate, a detergent builder.

In countries with acidic soils, such as Brazil, phosphate rock can be ground, sold, and distributed for direct application with limited improvements in soil productivity compared with applications of high-analysis soluble phosphate fertilizers.

ACKNOWLEDGMENTS

Data for the foreign mines and deposits in the evaluation were provided by Zellars-Williams, Inc., under contract J0100122. Data for mines and deposits in the Southeastern United States were developed by the former Bureau of Mines Eastern Field Operations Center in Pittsburgh, PA, in conjunction with Zellars-Williams, Inc. Data for the Western United States were developed by Bureau of Mines Field Operations Centers in Denver, CO, and Spokane, WA.

[5]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

WORLD PHOSPHATE INDUSTRY

PRODUCTION

Phosphate rock was produced in 29 countries during 1981 (table 1 and figure 1). The three main producers, the United States, the U.S.S.R., and Morocco, produced 104 million tons,[6] which was 72% of total world production. World production during 1981 was over 145 million tons--over 73% more than in 1971, and more than three times as much as in 1961.

Production from market economy countries[7] was just over 100 million tons during 1981, which was 70% of world production. During 1961 and 1971, production from countries with market economies was approximately 78% and 74% of world production, respectively. This shows a decline in the share of world production from market economy countries during the 20 years preceding 1981. Figure 2 illustrates the share of world phosphate rock production from the three major producing nations for the years 1961, 1971, and 1981.

[6] Unless otherwise noted, "tons" in this report refer to metric tons.

[7] Market economy countries are defined by the Bureau of Mines as all countries that are not centrally planned economy countries. Centrally planned economy countries comprise the following:

Albania	Kampuchea
Bulgaria	Korea, North
China	Laos
Cuba	Mongolia
Czechoslovakia	Poland
German Democratic Republic	Romania
Hungary	U.S.S.R.
	Vietnam

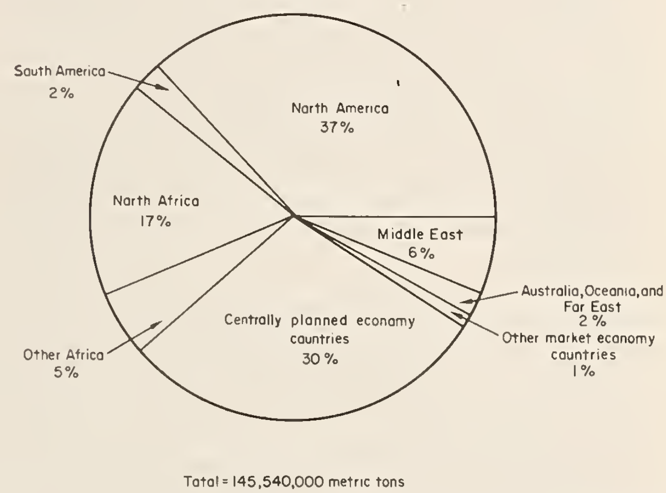


FIGURE 1. - 1981 world production of phosphate rock, by region.

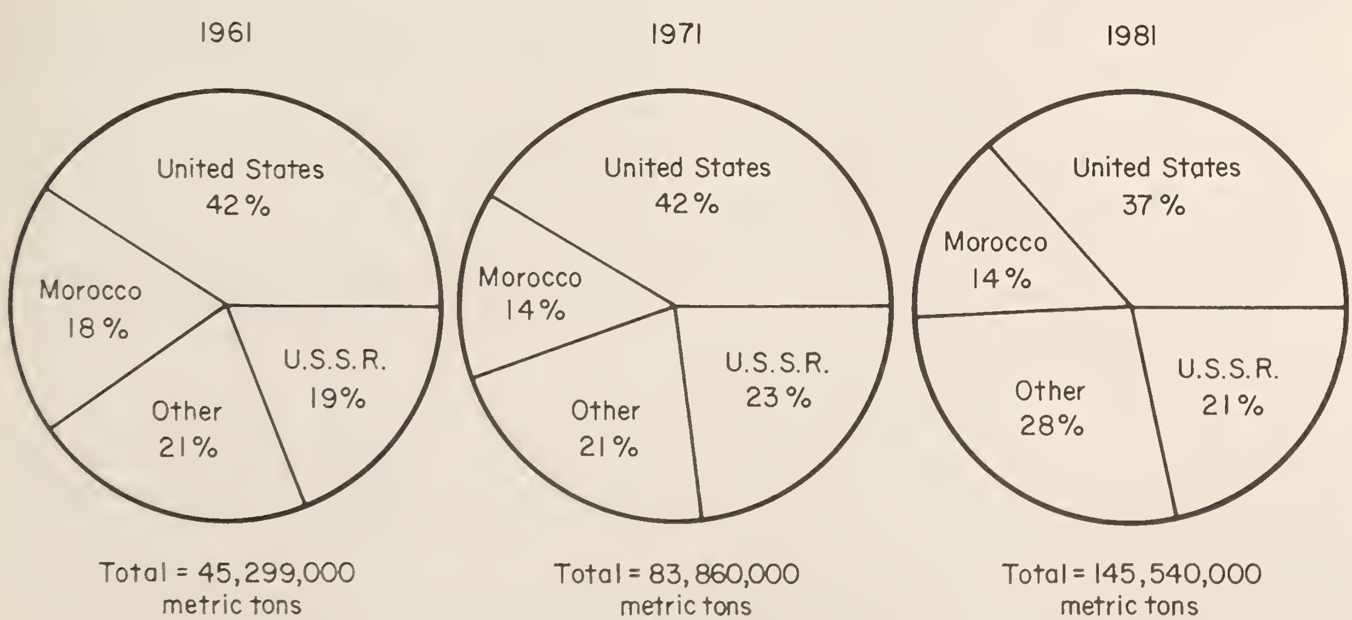


FIGURE 2. - Share of world phosphate rock production in 1961, 1971, and 1981: United States, Morocco, and U.S.S.R.

TABLE 1. - World production of phosphate rock, by region and country[1] (2-5)

(Thousand metric tons)

Region and country[2]	1961	1971	1981
Market economy countries:			
North America:			
Mexico	29	58	355
Netherlands Antilles (Curacao)	143	156	0
United States	18,856	35,270	53,624
Total[3]	19,029	35,484	53,979
South America:			
Brazil	659	200	2,637
Chile	14	0	0
Colombia	0	10	9
Venezuela	0	25	0
Total[3]	674	235	2,646
North Africa:			
Algeria	440	495	858
Morocco and Western Sahara	7,949	12,006	19,696
Tunisia	1,981	3,161	4,596
Total[3]	10,370	15,662	25,150
Other African countries:			
Senegal	574	1,545	2,017
South Africa, Republic of	297	1,233	2,910
Togo	118	1,715	2,244
Uganda	0	16	0
Zimbabwe	0	105	125
Total[3]	961	4,614	7,296
Middle East:			
Egypt	627	713	700
Israel	226	765	2,373
Jordan	423	569	4,244
Syria	0	6	1,321
Turkey	0	0	43
Total[3]	1,275	2,053	8,681
Oceania and Far East:			
Australia	5	6	15
Christmas Island	705	990	1,422
Indonesia	10	0	5
Kiribati (Banaba Island, formerly Ocean Island)	343	619	0
Makatea Island (French Oceania)	381	0	0
Nauru	1,303	1,867	2,000
Philippines	0	5	16
Total[3]	2,747	3,487	3,458
Miscellaneous countries:			
Belgium	14	0	0
Finland	0	0	130
France	81	19	25
Germany, Federal Republic of	0	60	0
India	20	243	550
Sweden[4]	0	0	75
Total[3]	116	322	780
Total market economy countries[3]	35,172	61,856	101,990
Centrally planned economy countries:			
China[e]	508	2,177	11,500
Korea, North[e]	152	272	550
Poland	47	0	0
U.S.S.R.[e]	8,799	19,002	30,950
Vietnam[e]	622	553	550
Total centrally planned economy countries[3]	10,127	22,004	43,550
Total world[3]	45,299	83,860	145,540

[e]Estimated.
[1]Purely guano deposits not included on this table.
[2]Some producing countries may not be listed because of small quantities.
[3]Data may not add to totals shown because of independent rounding.
[4]Swedish material is byproduct apatite concentrate derived from iron ore.

Phosphate production from North America, primarily the United States, was about 54 million tons in 1981. This was over 52% of the total production from market economy countries. During 1961, North America produced about 54% of the market economy total and during 1971 over 57%. Production from South America was less than 3 million tons during 1981, less than 2% of total market economy production.

Phosphate rock production from north Africa, over three-fourths of which was from Morocco, was 25 million tons during 1981. This was almost 25% of market economy production, nearly the same percent as 10 years ago. Twenty years ago, the north African share was almost 30%. Other African countries produced over 7 million tons during 1981, which was more than 5% of market economy output. These countries produced 7% 10 years ago, while 20 years ago they produced less than 3% of market economy production.

Phosphate rock production from countries in the Middle Eastern area, including Egypt and Turkey, was over 8 million tons during 1981, over 8% of market economy production. This share of market economy production is double that of 10 and 20 years ago.

Phosphate rock from Australia and Oceania during 1981 was over 3 million tons, which was over 3% of market economy production. The share of phosphate rock production from this area has declined from almost 6% during 1971 and almost 8% during 1961.

Production from other market economy countries historically totals less than 1% of total market economy production.

Phosphate rock production from centrally planned economy countries was over 43 million tons during 1981. This was 30% of world production, up from 26% during 1971 and 22% during 1961. The U.S.S.R. produced almost 31 million tons during 1981, over 71% of production from centrally planned economy countries. China produced over 11 millions tons, which is over 26% of centrally planned economy production. Production from centrally planned economy countries increased at a faster rate than production from the world as a whole between 1961 and 1981.

EXPORTS

World trade in phosphate rock during 1981 is shown in table 2 (2) and illustrated in figure 3. The table shows the destination of phosphate rock from eight major exporting areas to the major importing area of each. It must be noted that this table only shows exports of phosphate rock and not phosphoric acid or other processed products, and that these are to major importing areas and may omit small-volume exports to other areas. The phosphate rock that is not exported directly by a country is either consumed domestically or exported after further processing.

The table shows that during 1981, principal exports of the United States totaled nearly 9 million tons of phosphate rock, almost 17% of 1981 production. Morocco exported almost 15 million tons of phosphate rock, which was over 76% of its 1981 production. Algeria and Tunisia together exported 1.6 million tons, more than 29% of their combined domestic

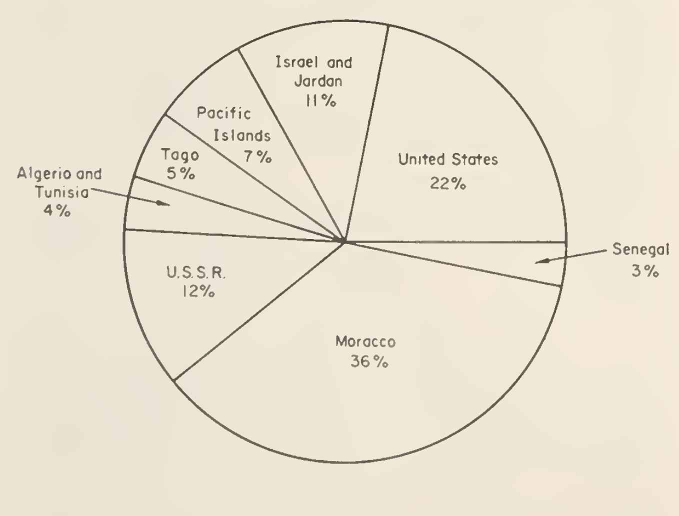


FIGURE 3. - Principal 1981 world exports of phosphate rock.

TABLE 2. - International trade in phosphate rock, 1981 (2)

(Includes only principal exporting sources and destinations)

Exporting source and destination of exports	Quantity, 10^3 metric tons
United States:	
Western Europe..........	3,525
Canada..................	3,200
Asia....................	1,486
South America...........	481
Eastern Europe..........	254
Total...............	8,946
Morocco:	
Western Europe..........	10,181
Eastern Europe..........	2,848
South America...........	1,103
Asia....................	859
Total...............	14,991
Algeria and Tunisia:	
Eastern Europe..........	807
Western Europe..........	794
Total...............	1,601
Israel and Jordan:	
Asia....................	1,962
Eastern Europe..........	1,438
Western Europe..........	1,431
Total...............	4,831
Senegal:	
Western Europe..........	826
Asia....................	215
Total...............	1,041
Togo:	
Western Europe..........	1,393
Eastern Europe..........	712
Total...............	2,105
U.S.S.R.:	
Eastern Europe..........	4,067
Western Europe..........	948
Total...............	5,015
Pacific Islands:	
Australia...............	1,767
New Zealand.............	853
Indonesia, Republic of Korea, Malaysia, Singapore, and Japan........	231
Total...............	2,851

production. Israel and Jordan together exported almost 5 million tons, which is 83% of their combined production. Senegal exported 1 million tons, almost 52% of production. Togo exported over 2 million tons, almost 95% of production. The U.S.S.R. exported over 5 million tons, about 16% of production. The Pacific Islands exported almost 3 million tons, 100% of production.

The United States exported significant quantities of chemical phosphate products during 1981. These included 1.5 million tons of greater than 40% superphosphates, 2,000 tons of less than 40% superphosphates, 3.9 million tons of diammonium phosphates, 1 million tons of less than 65% P_2O_5 phosphoric acid, 500,000 tons of more than 65% P_2O_5 phosphoric acid, and 28,000 tons of elemental phosphorus (3).

Morocco, which now exports mostly unprocessed phosphate rock, has plans to develop acid plants to increase the value of the phosphate rock before export.

OBJECTIVE

The United States has traditionally been the world's largest producer and net exporter of phosphate rock and related products. However, the U.S. producers are facing the challenge of foreign competition for export markets (primarily from Morocco), and rising production costs for Florida phosphate will make it more difficult to meet foreign competition in future years. This study was undertaken to assess the worldwide availability of phosphate rock, recognizing the critical importance of phosphorus to maintain agricultural production; and to compare the cost of producing phosphate rock in the United States with costs in other phosphate-producing nations.

A detailed study of the availability of phosphate from the United States, "Phosphate Availability--Domestic, A Minerals Availability Program Appraisal," was recently published (6). The data concerning U.S. mines and deposits in this world report are all from that study.

EVALUATION METHODOLOGY

For this study, a total of 201 mines and deposits were evaluated (130 domestic and 71 foreign). These deposits include resources of phosphate rock at the demonstrated level which can be mined and milled using current technology. An additional 17 mines and deposits in the U.S.S.R. and China, although not included in the evaluation, are discussed in this report. They were not included in the availability analysis owing to uncertainty as to the accuracy of the cost data.

Typically, beneficiated phosphate rock contains 7% to 20% moisture. Currently many processes to convert phosphate rock into its numerous end uses will accept wet rock feed, although less than 3% moisture is desirable. The final product in this study is defined as *dry* phosphate rock. For this study, the term "phosphate rock" refers to the beneficiated product, and "phosphate ore" refers to the minable material in the ground.

For purposes of consistency, it was assumed in the evaluation that all rock produced at a mine was transported to a local port for export unless that rock was being used for internal domestic consumption. If internally consumed, the rock was transported to a nearby acid plant or market. Typical world phosphate rock shipping charges are listed in the availability section later in this report. Additional costs for further processing of phosphate rock into its many end products were not included in the evaluation, although appendix A does discuss phosphoric acid production and related costs throughout the world.

The analysis methodology of this study follows:

1. The quantity and grade of phosphate ore resources were evaluated in relation to physical and technological conditions that affect production from each deposit as of the study date, January 1981.

2. The capital investments and operating costs for appropriate mining, concentrating, and processing methods were estimated for each mine or deposit.

3. An economic analysis of each operation determined its average total production cost over its entire producing life and the associated total demonstrated tonnage of phosphate rock that could potentially be recovered at specific production levels.

4. Upon completion of the individual property analyses, all properties included in the study were simultaneously analyzed and aggregated onto phosphate rock availability curves. These curves are aggregates of total potential phosphate rock that could be produced over the life of each operation, ordered from the lowest cost deposits to the highest. The curves illustrate the comparative costs associated with any given level of potential total output and provide an estimate of what the average long-run phosphate rock price (in January 1981 dollars) would have to be in order for a given tonnage to be potentially available. The long-run price that each operation would require to cover its average total cost of phosphate rock production would provide revenues sufficient to cover the average total cost of production, including a return on investment high enough to attract new capital. The rate of return used in this study is a 15% discounted cash flow rate of return (DCFROR) on the total investments of each operation.

The data collected for this report are stored, retrieved, and analyzed in a computerized component of the Bureau of Mines Minerals Availability Program.

After a deposit was selected for the analysis, an evaluation of the operation was begun. The flow of the Minerals Availability evaluation process from deposit identification to analysis of availability information is illustrated in figure 4.

Selection of deposits was limited to known deposits that have significant demonstrated reserves or resources. Reserves are material that can be mined, processed, and marketed at a profit under prevailing economic and technological conditions. Resources are concentrations of naturally occurring solid, liquid, or gaseous materials in the Earth's crust in such form that economic extraction of a commodity is currently or potentially feasible (7). Information on the individual phosphate mines and deposits included in this study (such as ownership, status, deposit type, grade, and capacity) is in appendix B.

For the deposits analyzed, tonnage estimates were made at the demonstrated resource level based on the mineral resource-reserve classification system developed jointly by the Bureau of Mines and the U.S. Geological Survey (7). The demonstrated resource category includes measured plus indicated tonnages (fig. 5). Generally, reserve and resource tonnage and grade calculations presented in this paper were computed from specific measurements, samples, or production data, and from estimations made on geologic evidence.

To be included in the analysis, U.S. phosphate deposits had to meet technological criteria representing current acceptable U.S. industry standards at the time of the analysis. The criteria shown below for the southeastern deposits should be viewed as guidelines rather than an absolute lower limit (8). Although not used in this study, a new set of criteria for classifying phosphate rock resources has recently been completed (9). In the current criteria, an exception is made to the deposit size requirement if the deposit is adjacent to larger identified deposits or is in a hardrock area. In the first three cases below the stipulated radius equates to the resource ore body covering one-half of the area of the deposit, at an average of 2,500 tons per acre (6).

1. Deposit size must be more than 5 million tons of recoverable phosphate rock, and this rock must be within an

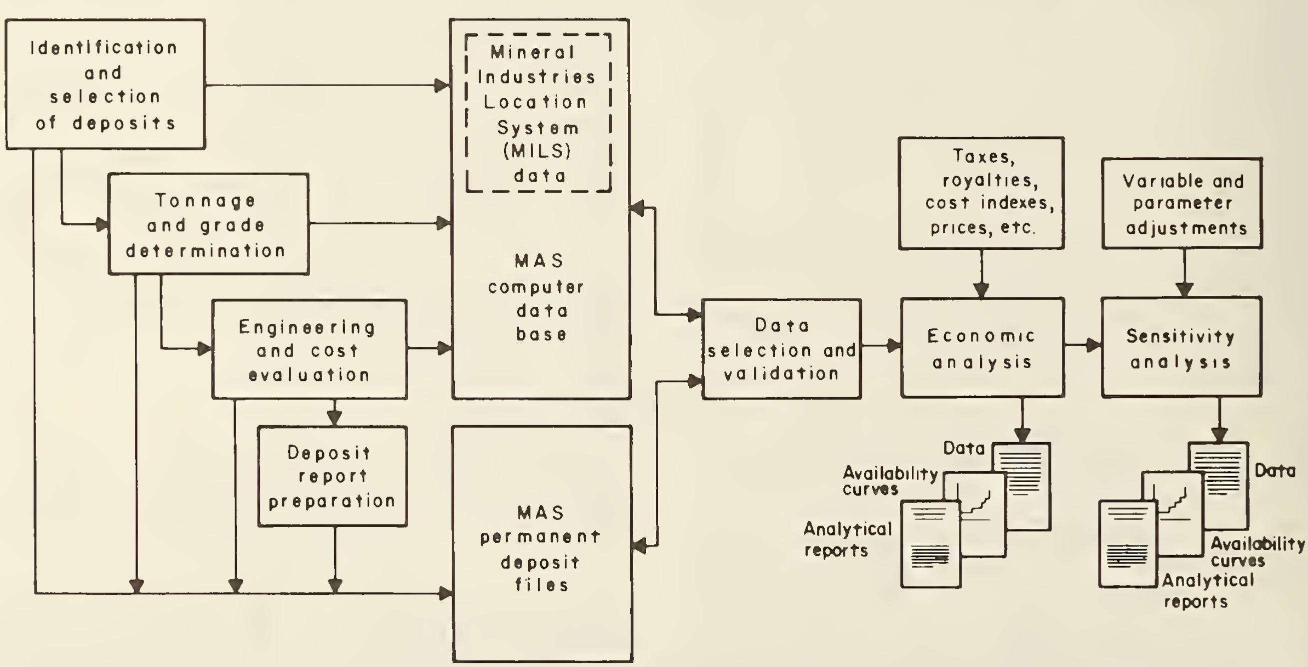


FIGURE 4. - Flow chart of evaluation procedure.

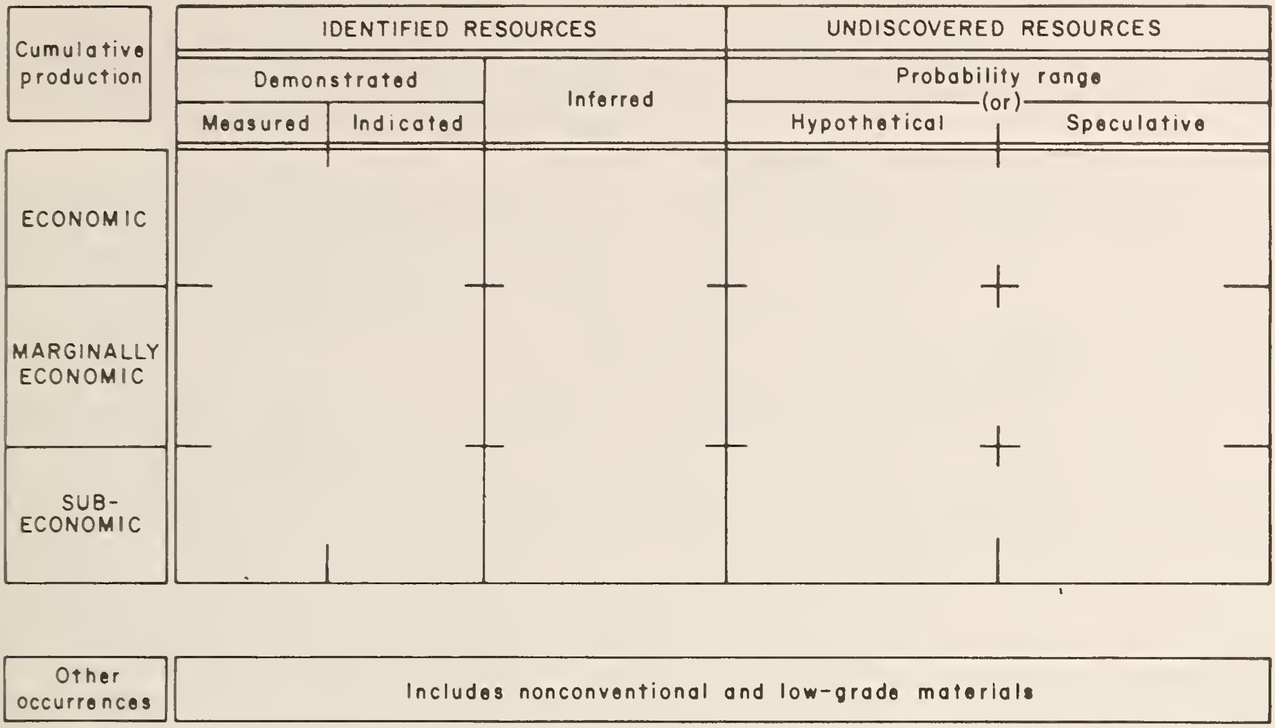


FIGURE 5. - Mineral resource classification categories.

average radius of 1.5 miles from the center of the ore body.

2. Deposit size must be more than 10 million tons of recoverable phosphate rock if the average overburden thickness is more than 6 m, and this rock must be within an average radius of 2.5 miles of the ore body centroid.

3. Deposit size must be greater than 15 million tons of recoverable phosphate rock if the overburden average thickness is more than 9 m, and this rock must be within an average radius of 2.5 miles from the center of the ore body.

4. The flotation feed grade must be more than 4.6% P_2O_5.

5. The concentrate grade must be more than 27.5% P_2O_5.

6. The phosphate concentration must be 1 ton of recoverable product per 8 m^3 of ore.

7. The ore zone must be more than 2 m thick.

8. Phosphate rock product must contain less than 1.5% magnesium oxide (MgO). (Resources of high-MgO phosphate deposits were quantified in this report and technological developments are discussed, but deposits containing greater than 1% MgO were not evaluated in this study.)

The following criteria for developing resource estimates of Tennessee phosphate represent a range that the central Tennessee phosphate companies recognize as those representing acceptable minable deposits (6):

1. A minimum cutoff grade range of 16% to 17.2% P_2O_5.

2. Minimum ore thickness range of 0.6 to 1.2 m.

3. Maximum overburden-to-ore ratio range of 3:1 to 4:1.

4. A minimum ore body size of 22,675 dry tons of phosphate rock.

The average ore body is small--150,000 to 1.2 million tons--which means that deposits at a number of separate locations may have to be mined to satisfy one company's annual requirement.

The study criteria for explored deposits in Utah and Wyoming include a minimum ore thickness of 0.91 m and a minimum average grade of 18% P_2O_5. For economic classification, minable resources were further subdivided by depth, thickness, dip, grade, and probability of occurrence. Resources above adit entry level[8] were estimated and economically evaluated after site-specific corrections were applied. The quantity of resources occurring below adit entry level was not costed or economically evaluated in this study because of its extremely high recovery cost.

The foreign deposits included in the analysis had to meet the following criteria:

1. Producing properties accounting for at least 85% of the phosphate rock production from each significant world producing country.

2. Developing and explored deposits where the demonstrated phosphate rock reserve-resource quantity was equivalent to at least the lower limits of the reserve-resource quantity of the producing deposits.

3. Past producing deposits where the remaining demonstrated phosphate rock reserve-resource quantity was equivalent to at least the lower limits of the reserve-resource quantity of the producing deposits.

Evaluation of each phosphate property included determining phosphate resources, deposit development, technologies, and costs. Information on the average grades, ore tonnages, and different physical characteristics affecting production from domestic phosphate deposits was obtained from numerous sources, including Bureau of Mines and Geological Survey publications, professional journals, State and industry publications, annual reports, company 10K reports, prospectuses filed with the Securities and Exchange Commission, data made available to the Bureau of Mines by private companies (domestic and foreign) or via contract, and estimates made by Bureau personnel based on personal knowledge and judgments.

GEOLOGY AND RESOURCES

Following is a discussion of the deposits evaluated as part of this study. For nearly every country, a brief discussion is included for each deposit evaluated; however, for certain countries such as Morocco and the U.S.S.R., where it is impractical to mention each deposit individually, the geology and resources of the regions containing several deposits are discussed.

Demonstrated resources used in the analysis are listed in table 3 and shown graphically on figure 6. Not all numbers in table 3 agree precisely with those contained in the text, as text numbers were obtained directly from published sources, whereas the table shows numbers derived from data obtained for this analysis, some of which are confidential. Confidential figures, however, are included within aggregated numbers in the table.

Morocco has an enormous phosphate resource, accounting for over 56% of the total demonstrated resource included in this analysis and for nearly 59% of total demonstrated resources in market economy countries. The United States is a distant second, with approximately 19% of total market economy countries' demonstrated resources. Based on Bureau of Mines estimates of long-term world demand for phosphate rock, which is projected to grow at an average annual rate of 3.2% through the end of the century to a cumulative total of approximately 3.7 billion

[8]The adit entry level is defined as the nearly horizontal access to the minable resource. The adit level also serves as a conduit for natural mine water drainage.

TABLE 3. - Summary of world demonstrated phosphate resources as of January 1981

Region and county	In situ ore tonnage, 10^6 metric ton	In situ grade, wt % P_2O_5	Recoverable rock product, 10^6 metric ton	Rock product grade, wt % P_2O_5
Market economy countries:				
North America:				
Canada	120	20	35	39
Mexico	1,127	5	121	31
United States	27,462	10	6,382	30
Total	NAp	NAp	6,538	NAp
North Africa:				
Morocco and Western Sahara	38,143	30	20,920	32
Tunisia and Algeria	741	26	375	31
Total	NAp	NAp	21,295	NAp
Middle East:				
Egypt	1,757	26	1,026	28
Israel	179	26	91	33
Jordan	1,194	27	525	33
Syria, Iraq, Saudi Arabia, and Turkey	1,167	23	492	32
Total	NAp	NAp	2,134	NAp
Oceania:				
Australia (including Christmas Island)	1,516	18	551	34
Nauru	26	38	16	39
Total	NAp	NAp	567	NAp
South America:				
Brazil:				
Igneous	2,130	9	270	36
Sedimentary	531	13	136	35
Colombia, Peru, and Venezuela	2,612	7	248	30
Total	NAp	NAp	654	NAp
West Africa: Senegal and Togo	640	29	183	34
Southern Africa:				
Angola and Zimbabwe	50	14	11	35
Republic of South Africa	21,496	6	2,638	37
Total	NAp	NAp	2,832	NAp
Other market economy countries:				
India, Finland, Pakistan	([1])	([1])	158	36
Total market economy countries	NAp	NAp	34,178	NAp
Centrally planned economy countries:				
China	337	26	208	28
U.S.S.R.				
Igneous	2,699	14	654	39
Sedimentary	2,354	14	679	28
Total centrally planned economy countries	NAp	NAp	1,541	NAp
Total world	NAp	NAp	35,719	NAp

NAp Not applicable.

[1]In situ tonnage and grades not averaged because of combining deposits of different geologic types.

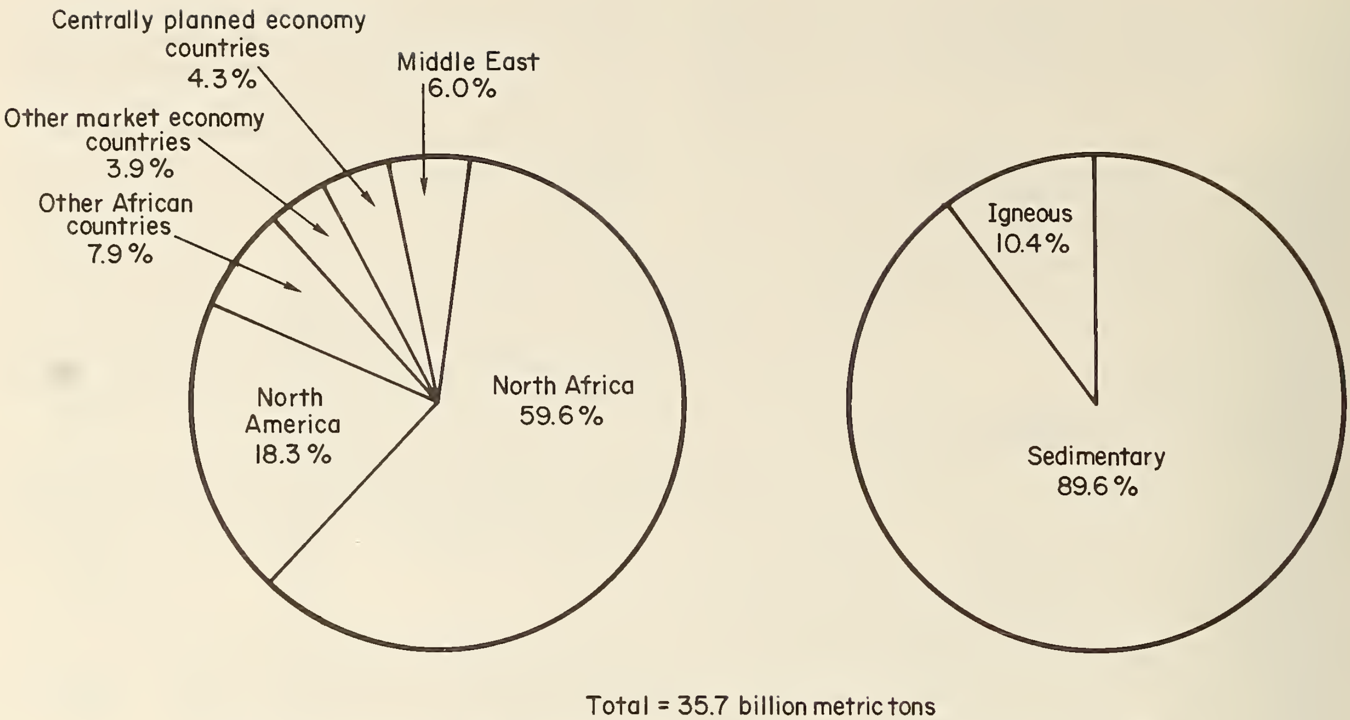


FIGURE 6. - Demonstrated phosphate rock resources, by region and geologic type.

tons (2), Morocco alone has sufficient resources to provide for world demand far into the future.

On the basis of geologic type, sedimentary deposits contain nearly 90% of the total demonstrated resource of 35.7 billion tons. Significant igneous deposits, which account for the remaining demonstrated resources, are located in Canada, Brazil, South Africa, Finland, and the Soviet Union.

U.S. demand is expected to grow at an average annual rate of 2% in the future (2). Given the necessary productive capacity, the United States can meet its needs into the next century.

The United States has inferred resources estimated on the order of 7 billion tons, while the total for all market economy countries is over 20 billion tons. In addition to the demonstrated and inferred resources evaluated as part of this study, the Bureau of Mines and U.S. Geological Survey have reported that there is a total of about 95 billion tons of phosphate rock resources in the world (10). These include inferred, hypothetical, and speculative resources.

NORTH AMERICA

United States

The United States is the world's largest producer of phosphate rock, accounting for nearly 54 million tons in 1981. The geology and resources of U.S. phosphate have been treated in a recent Bureau publication (6) and are not addressed in detail here. However, a brief summary is warranted to provide a comparison of geology and resources of U.S. phosphate with those of the rest of the world.

U.S. phosphate resources are concentrated in two geographical areas: the Southeast (especially Florida and North Carolina) and the West (Idaho, Montana, Utah, and Wyoming) (fig. 7). Phosphates in Florida, Georgia, and South Carolina are in the Hawthorn Formation of middle Miocene age, and in the Bone Valley Formation and younger formations that consist of reworked Hawthorn sediments. The important commercial deposits consist of pebble- and sand-size grains of carbonate fluorapatite and quartz in a clay- and silt-size matrix.

Deposits in North Carolina are in the middle Miocene Pungo River Formation and consist of carbonate fluorapatite pellets, quartz sand, and minor clay and carbonate.

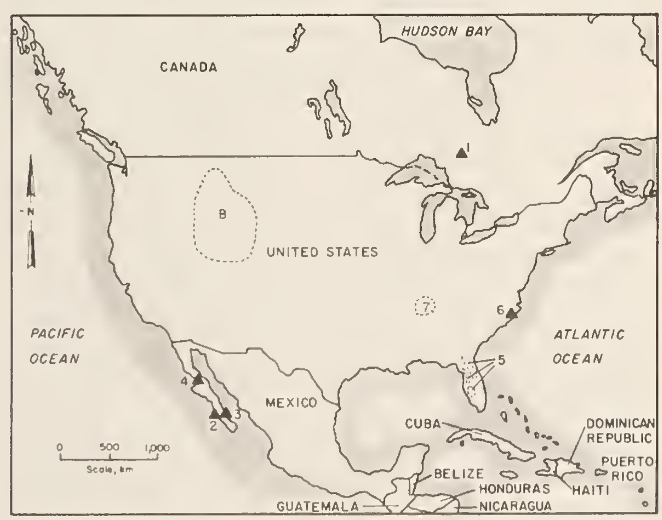
The central land-pebble district in central Florida has been the largest producer of phosphate in the world for many years. The deposits there have an ore zone ranging in thickness from 3 to 8 m, with overburden of 3 to 10 m. Total demonstrated in situ resources for the Southeastern United States are 23 billion tons at an average grade of 7% P_2O_5, resulting in approximately 4 billion tons of recoverable product. There are estimated to be an additional 6 billion tons of product at the inferred level (6).

The phosphate deposits of the Western United States occur in the Permian Phosphoria Formation, with phosphate rock composed primarily of carbonate fluorapatite pellets, oolites, pisolites, nodules, and bioclasts. Ore is mined principally from the upper and lower zones of the Mead Peak Member. The two zones range in thickness from 9 to 18 m and are separated by the sandstone, shale, and carbonate of the middle zone, which typically is 30 m thick. Overburden is commonly 5 to 10 m thick. Only the altered rock portion of the total resources was evaluated as part of this study because unaltered phosphate-bearing rock contains high amounts of impurities (magnesium and iron) and is presently uneconomic. Total demonstrated in situ resources for the deposits evaluated are 4.9 billion tons averaging 21.3% P_2O_5, resulting in 2.5 billion tons of product. There is an additional 1 billion tons of recoverable product at the inferred level, most of which is unaltered (6).

Canada

Phosphate in Canada occurs mainly as accessory apatite in carbonatite in northern Ontario and western Quebec. The Ontario Carbonatite Province contains some 50 known carbonatite complexes over an area of 1.3 million km^2. All carbonatite complexes that have been examined for their mineral potential contain apatite grading from 5% to 25% P_2O_5. Some have been enriched in apatite by removal of carbonate by leaching. Only the Cargill deposit (fig. 7) was evaluated for this study because it is the only deposit that has been studied in sufficient detail to allow for a complete analysis and is the most promising in terms of its potential as a future phosphate producer.

The Cargill deposit, located 640 km northwest of Toronto, was discovered in 1975. It is a high-grade residual phosphate on a karst topography. The deposit is covered by a layer of glacial lake clay averaging 7 m in thickness, and sand, clay, gravel, and silt from 0 to 130 m thick. The residual phosphate deposit reaches up to 170 m thick in troughs and sinks but is missing or very thin on topographic highs. In situ resources, assumed to be demonstrated for this study, are about 120 million tons.



LEGEND

▲ Discrete individual deposits

Several deposits within a district

FIGURE 7. - Location map, North American deposits. *1*, Cargill; *2*, San Hilario (inferred only); *3*, San Juan de la Costa; *4*, Santo Domingo; *5*, Florida; *6*, North Carolina; *7*, Tennessee; *8*, Western United States (Idaho, Montana, Utah, Wyoming).

Grade has been reported to average 19.6% P_2O_5 (11).

Mexico

Mexico has several phosphate deposits. Those that were evaluated are located on the Baja California peninsula. The most significant deposits, San Juan de la Costa (producer) and Santo Domingo (under development), were evaluated at the demonstrated level. Together they contain 121 million tons of recoverable phosphate rock. San Hilario, a nonproducer, has only inferred resources at this time. Locations of the three deposits are shown in figure 7. The La Negra property, located in Hidalgo State at Zimapau, although accounting for a portion of Mexico's annual production, was not included in this study because of its insignificance on a world scale.

San Juan de la Costa is 100 km north of La Paz on the eastern coast of Baja California Sur. It was discovered in 1976, and production began in January 1981. The phosphorite is in the lower Miocene Monterrey Formation, which consists of alternating beds of sandstone, clayey sandstone, sandy shale, shale, and siltstone. The formation's two members attain a combined maximum thickness of 110 m. The lower member is 70 m thick and contains some phosphatic oolite beds that grade 1% to 9% P_2O_5. The upper member contains the economic phosphate beds. The phosphatic zone consists of five horizontal beds which range in thickness from 0.8 to 1.5 m; the thickest and most economical bed is referred to as the Humboldt Superior, with a thickness of 1.5 m and an average P_2O_5 content of 19%. The deposit is reported to contain 50 million tons of in situ reserves averaging 18% to 20% P_2O_5 (12).

The Santo Domingo deposit, 110 km north-northwest of La Paz along the Pacific coast of Baja California Sur, consists of phosphate pellets in recent beach sands. The pellets were derived from Miocene sediments. In situ reserves are estimated to be more than 1 billion tons averaging about 5% P_2O_5 (13). Only about 4% of the total 1,500-km^2 phosphate-bearing area had been explored in detail by 1979, and there are presumed to be substantially more resources in the deposit.

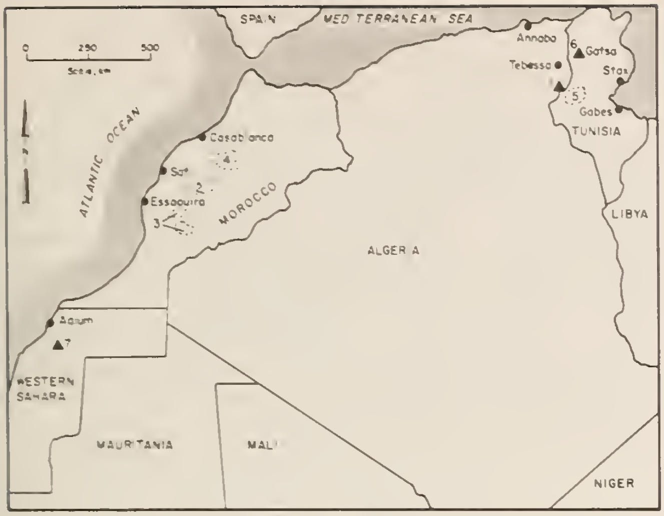
San Hilario is situated in the center of the Baja California peninsula, 80 km west-northwest of La Paz. The phosphatic zones occur within the Monterrey Formation and consist of two well-defined beds, each of which is about 0.5 to 1.2 m thick. Inferred in situ resources at San Hilario total 760 million tons averaging 14% P_2O_5 (14). The deposit was discovered in 1974, but its unfavorable location and problems in beneficiation and mining have resulted in a decision to forego development.

NORTH AFRICA

Morocco

Morocco is the world's largest exporter and third largest producer of phosphate rock, with a 1981 production of 19.7 million tons. It has enormous resources, with over 20 million tons of recoverable phosphate rock at the demonstrated resource level, or 56% of the total contained in deposits evaluated for this study. Inferred resources in Morocco total about 5 billion tons of recoverable product, part of which cannot be beneficiated at the present time. Moroccan deposits are located in three regions: the Oulad Abdoun Plateau, the Ganntour Plateau, and the Meskala district (figs. 8-9). Production of phosphate began in 1921 near the town of Khouribga on the Oulad Abdoun Plateau, where the country's richest and most extensive deposits occur. Production from the Ganntour Plateau began in 1932 at Youssoufia, while the Meskala phosphates, although discovered in 1908, have yet to be exploited. Morocco plans to begin production there by the late 1980's.

All three phosphate-bearing regions lie within a northeast-southwest-trending belt of Upper Cretaceous and Eocene sediments, about 350 km long. The main phosphatic suite on the Oulad Abdoun Plateau

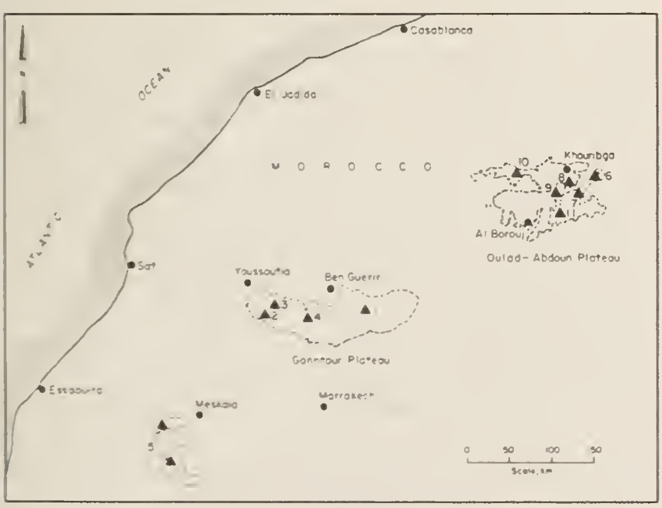


LEGEND

▲ Discrete individual deposits

Several deposits within a district

FIGURE 8. - Location map, north African deposits. *1*, Djebel Onk; *2*, Ganntour Plateau; *3*, Meskala District; *4*, Oulad Abdoun Plateau; *5*, South Basin (Kef Eschfair, M'Dilla, Metlaoui, M'Rata, Moulares, Redeyef, and Sehib); *6*, Kalaa Khasba; *7*, Bou Craa.



LEGEND

▲ Discrete individual deposits

Several deposits within a district

FIGURE 9. - Location map, Moroccan deposits. *1*, Ben Guerir (Ben Guerir, El Outa, Nzala, Tessaout); *2*, Youssoufia Black Rock; *3*, Youssoufia Open Cast; *4*, Youssoufia White Rock; *5*, Meskala District (Chichaoua and Imi N'Tanoute); *6*, Daoui Nord; *7*, Daoui-Recette 4; *8*, Khouribga Underground; *9*, Meraa El Arech; *10*, Sidi Hajjaj; *11*, Southern Khouribga Region.

consists of sandy oolitic beds alternating with marl, clay, phosphatic limestone, and some chert. The ore zone ranges in thickness from 50 m in the south at Al Borouj, where 10 distinct beds are present, to about 25 m at Khouribga in the north. Total demonstrated in situ resources on the Oulad Abdoun Plateau are about 7 billion tons at an average grade of 30% P_2O_5.

The Ganntour Plateau is southwest of the Oulad Abdoun Plateau (fig. 9). Although the phosphatic section thins from west to east, there is an increase in the number of beds of high enough grade and thickness to warrant exploitation; thus, the average ore zone thickness at Youssoufia (west end), where mining is confined to one bed, is less than 3 m, whereas at Ben Guerir, several kilometers east of Youssoufia, the ore zone reaches a maximum of 50 m (average, 12 m), and there are 23 beds in the section. Overburden thickness ranges from an average of 6 m at Ben Guerir to an average of 50 m at Youssoufia, where underground mining has proceeded to the south into an area of increased overburden thickness. Total demonstrated in situ resources in the Ganntour Plateau region are about 11 billion tons averaging about 30% P_2O_5.

Phosphate resources in the Meskala district occur on the northern slope of the High Atlas range, near Imi N'Tanoute, and farther north near Chichaoua. The main phosphate beds contain a total of 18 billion tons of demonstrated in situ resources averaging nearly 32% P_2O_5. Near Imi N'Tanoute, the beds have been folded and faulted. This situation will render mining a difficult undertaking relative to the other Moroccan deposits, which are essentially flat-lying.

Morocco is pursuing a policy of expanding phosphate production and constructing facilities to convert phosphate rock to phosphoric acid. A new port and acid plant complex, Jorf Lasfar located at El Jadida, is expected to accommodate production increases from areas currently exploited, while a new port will probably be built at Essaouira to handle future production from the Meskala district. In addition, Morocco plans to begin extraction of uranium from acid produced at Safi, where the first such plant is to be built.

Western Sahara

The Bou Craa deposit is in the El Aaiun Basin, 100 km inland from the port of Aaiun (fig. 8). It was discovered in 1947, production began in 1972 but was severely curtailed in 1976 following sabotage of the 100-km-long conveyor system used to transport rock from the deposit to Aaiun. The operation was completely inactive in 1980 and 1981, but was restarted late 1982.

The Bou Craa deposit is in Upper Cretaceous and Paleocene sediments in the northern end of the Aaiun Basin. At Bou Craa Wadi, where the richest phosphates occur, the grade averages 32% P_2O_5, and the ore zone is 5 to 6 m thick. Total in situ resources, assumed to be demonstrated for this study, are 1.6 billion tons (15). Overburden consists mainly of quartz sand and silt, with some calcareous conglomerate and limestone. Thickness varies from 0 to 40 m, averaging 18 m.

Algeria

The most important phosphate resources in Algeria are at Djebel Onk, 320 km south of the port of Annaba (fig. 8). Phosphate has been mined in Algeria since its discovery in the late 1800's, but mining at Djebel Onk, which accounts for over 90% of the country's production, began in 1967. The other Algerian mine, Djebel Koif, has a long history of production, but is nearly exhausted. Only Djebel Onk was evaluated as part of this study.

Phosphate beds at Djebel Onk, upper Paleocene in age, are exposed in two anticlinal structures, where the ore zone averages about 30 m thick. Overburden thickness ranges from 0 to 120 m, averaging 25 m. In situ reserves have been conservatively estimated to be about 500 million tons (15) at an average grade of nearly 25% P_2O_5.

Algeria plans to nearly double production at Djebel Onk by 1986 to provide phosphate rock for expanded acid plant facilities at Annaba and Tebessa; however, expansion plans were temporarily shelved in 1982. Water used to process the ore must be piped 90 km to Djebel Onk, and availability of water could limit further production.

Tunisia

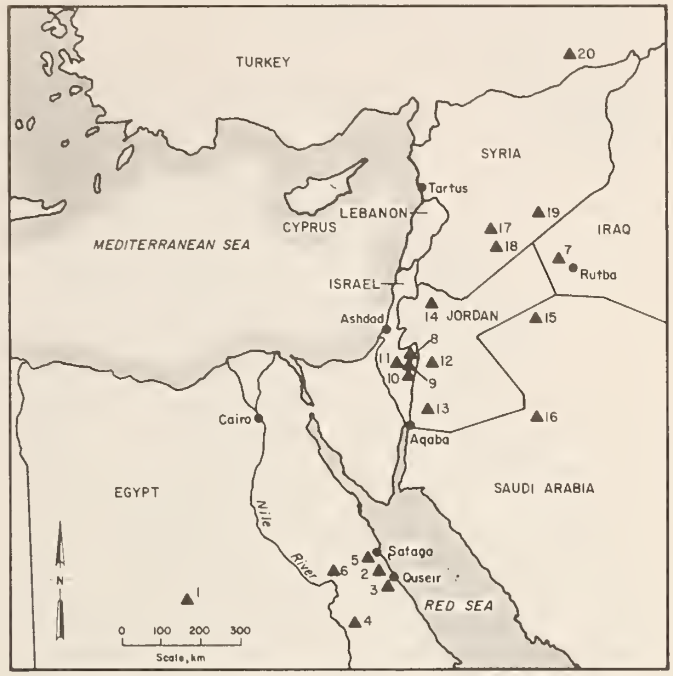
Phosphate was first produced in Tunisia in the late 1800's. There are eight active mines, seven of which are in the Gafsa area: Kef Eschfair, M'Dilla, Metlaui, M'Rata, Moulares, Redeyef, and Sehib (fig. 8). The eighth mine, Kalaa Khasba, is in the Tebessa-Thala area. Total demonstrated recoverable phosphate rock resource for the eight deposits studied is 126 million tons.

The seven Gafsa mines are in the South Basin, an area of 129 km by 40 km with an east-west axis. Phosphates are contained in upper Paleocene to lower Eocene limestone and marl within an east-west-trending series of anticlines and synclines with average dips of 20°. There are nine phosphate-bearing beds, not all of which are present everywhere in the basin. Individual beds range from 1 to 10 m in thickness; ore zone thickness ranges from 2 m at Redeyef and Sehib to 10 m at Kef Eschfair. All but Kef Eschfair are underground operations, with overburden thicknesses averaging from 100 to 200 m. Overburden thickness averages 25 m at Kef Eschfair.

In addition to the operations listed above, Tunisia plans to begin operations at four other areas (with a total of 393 million tons of inferred in situ resources) by 1990. The four areas are Djellabia, Kef Eddour, Oum el Kecheb, and Sra Ouertane (16). All but Sra Ouertane are located in the Gafsa area. They were not evaluated because of insufficient data at the time of this study.

MIDDLE EAST

Twenty-two deposits in seven Middle Eastern countries were considered for this study. Those that contain only inferred resources were only quantified, not evaluated with respect to cost. Countries containing deposits and number of deposits evaluated follow: Egypt (7), Iraq (1), Israel (4), Jordan (4), Saudi Arabia (2), Syria (3), and Turkey (1). All deposits studied lie within a belt of Upper Cretaceous sediments that stretches from Turkey to Morocco (fig. 10). Total recoverable phosphate rock resources in Middle East deposits evaluated are 2,135 million tons at the demonstrated level.



LEGEND

▲ Discrete individual deposits

FIGURE 10. - Location map, Middle Eastern deposits. *1*, Abu Tartur; *2*, Hamrawein; *3*, Quseir; *4*, Sabaiya West and East; *5*, Safaga; *6*, Qena (inferred only); *7*, Akashat; *8*, Arad; *9*, Ein Yahav (inferred only); *10*, Nahal Zin; *11*, Oron; *12*, El Hasa-El Abiad; *13*, Esh Shidiya; *14*, Ruseifa; *15*, Turayf (inferred only); *16*, West Thaniyat; *17*, Kneifess; *18*, Sharkya; *19*, Tarag El Hbari (inferred only); *20*, Mardin-Mazidag.

Egypt

Phosphate in Egypt is contained in three areas: the Nile Valley, the Red Sea area, and the Western Desert. Evaluated deposits that contain resources at the demonstrated level include Abu Tartur, Hamrawein, Quseir, Safaga, and Sabaiya East and West. Also included in the study is the Qena deposit, with resources only at the inferred level. All but Abu Tartur and Qena are producing. Sabaiya West is a surface operation. All other producing deposits are underground operations owing to the thickness of overburden, which averages in excess of 100 m. The bulk of Egyptian production comes from Safaga and Quseir, near the Red Sea. Phosphate has been known in the Western Desert of Egypt since the late 1800's, but because of the remote location, Abu Tartur, a potential producer, may be the first mine in that area. Mining in the Nile Valley, where the Sabaiya properties are located, began in 1908. Ore zone thicknesses range from an average of less than 2 m at Hamrawein and Quseir to over 14 m at Safaga. The average thickness at Abu Tartur is 9 m; at Sabaiya it is 8 m. Total demonstrated in situ resources in the deposits studied are 1,757 million tons at an average grade of 26% P_2O_5. Including Qena, Egypt contains an additional 221 million tons of recoverable product at the inferred level. A special problem regarding most Egyptian deposits is the high level of contaminants such as iron, aluminum, magnesium, and chlorine.

Iraq

Akashat is the first mine to exploit the vast deposits of the Western Desert of Iraq, where phosphates were discovered in 1955. It was the only Iraqi deposit evaluated for this study. It is north of Rutba, where phosphates occur in Upper Cretaceous and lower Eocene sediments of the Tayarat and Um-er-Radkuma Formations. Ore zone thickness averages 10.5 m, with 5.5 m of overburden. There are reported to be 450 million tons of proven in situ reserves averaging 21% P_2O_5 (<u>17</u>).

Israel

Four Israeli deposits were evaluated, three of which (Arad, Nahal Zin, and Oron) are producing. The fourth, Ein Yahav, is a nonproducer with resources known only at the inferred level. The nearly depleted Makhtesh deposit, which provides phosphate rock for superphosphate production, was also not evaluated for this study. Total demonstrated in situ resources for the producing deposits are 179 million tons averaging 26% P_2O_5. Including resources at Ein Yahav, there is an additional 126 million tons of recoverable product at the inferred level. All deposits are Upper Cretaceous in age and are exposed in a series of anticlines and synclines that traverse the Negev Desert. Deposits of commercial size are preserved within the synclinal basins. All production is by surface methods, as overburden thicknesses do not exceed 30 m. Ore zone thickness ranges from an average of 5.7 m at Oron to about 10 m at Arad. The high carbonate and organic content of the Oron deposit dictates that the ore must be calcined if used to produce wet-process phosphoric acid.

Jordan

The important phosphate deposits of Jordan occur in the marine Belqa Series that ranges from Upper Cretaceous to Eocene in age. There are three producing deposits (El Abiad, El Hasa, and Ruseifa) and one developing deposit (Esh Shidiya) in the country. Demonstrated in situ resources for deposits evaluated in this study total nearly 1.2 billion tons averaging 27% P_2O_5 (533 million tons of recoverable product). Maximum overburden depth does not exceed 40 m; thus all deposits are mined using strip level methods. Ore zone thicknesses range from an average of 5 m at El Hasa and El Abiad to 8 m at Esh Shidaya. All Jordanian deposits contain substantial amounts of chlorine, which can be removed by washing the ore.

Saudi Arabia

Only one deposit in Saudi Arabia was evaluated at the demonstrated level. West Thaniyat contains in situ resources totaling 225 million tons of 22% P_2O_5. The West Thaniyat phosphate and that at Turayf (inferred only) are contained in the phosphatic sediments of the Hibr (Paleocene-Eocene) and Aruma (Cretaceous) Formations.

Syria

Syria has two producing deposits, Kneifess and Sharkya, which contain demonstrated in situ resources totaling 412 million tons at 25% P_2O_5. Production of Syrian phosphate begain in 1971 with development of the Kneifess deposits. Geology of the deposits is similar to that of those in neighboring Jordan and Iraq, with economic phosphates contained in Upper Cretaceous and Eocene sediments. In addition to Kneifess and Sharkya, the Tarag El Hbari deposit was evaluated, although only at the inferred level. The deposit is located in the area of the Rutbeh Uplift, 250 km northwest of Damascus. It contains over 150 million tons of inferred recoverable phosphate rock resources (15).

Turkey

The only Turkish deposit included in this analysis is Mardin-Mazidag, where there are three main phosphate beds totaling 1.8 m in thickness. Overburden thickness averages 15 m. Production is from oolitic limestones of the Kasrik Formation of Upper Cretaceous age. Estimated in situ resources in the Mardin-Mazidag area were reported to total 258 million tons at 10% P_2O_5 (15); about 80 million tons, averaging 18% P_2O_5, was considered to be demonstrated for purposes of this study.

OCEANIA

Australia and Christmas Island

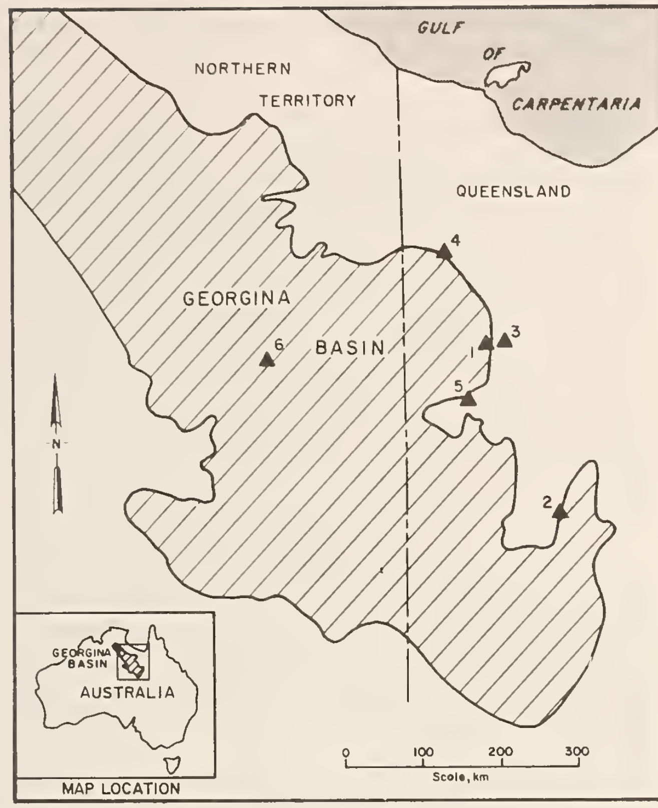
Australia has two major sources of phosphate resources, Christmas Island and the Georgina Basin in Queensland and Northern Territory (figs. 11-12). Total demonstrated recoverable resources of phosphate rock are 551 million tons, less

LEGEND

▲ Discrete individual deposits

Several deposits within a district

FIGURE 11. - Location map, Nauru and Christmas Island deposits.



LEGEND

▲ Discrete individual deposits

FIGURE 12. - Location map, Australian (Georgina Basin) deposits. *1*, D Tree; *2*, Duchess; *3*, Lady Annie-Lady Jane; *4*, Northern deposits; *5*, Sherrin Creek-Lily Creek (inferred only); *6*, Wonarah (inferred only).

than 2% of the total contained in deposits evaluated for this study.

Christmas Island is an isolated volcanic seamount in the Indian Ocean with a total area of 21.5 km^2. Phosphate has been produced here from 1890 to the present. Host rock for the phosphate deposit is a coral limestone that forms a pattern of pinnacles. Phosphatic layers average 6 m in thickness and consist of three types of phosphate, designated A, B, and C. The A grade is calcium phosphate (apatite) averaging 35% P_2O_5 and occurs between and overlying the limestone pinnacles at the base of the phosphate section. Types B and C overlie type A. C-grade rock is an aluminum-rich phosphate subsoil, while type B is transitional, effectively a mixture of A and C. A and B are normally regarded as commercial grades; C is not, although limited amounts are occasionally produced for local markets.

Phosphate deposits in the Georgina Basin in northwest Queensland and Northern Territory are associated with silt, chert, and silicified coquina of the Beetle Creek Formation of Middle Cambrian age, or its lateral equivalents, the Border Water Hole Formation in Queensland and the Wonarah and Burton Beds in Northern Territory. The phosphate is either pelletal or extremely fine grained and is often referred to as collophane mud. Fifteen distinct deposits have been identified since the initial discovery near Duchess in 1966.

The Duchess deposit is 140 km south of Mount Isa and consists of a series of phosphate beds of varying grades with a total average thickness of 11 m. Overburden ranges from 0 to 150 m. Total in situ resources have been estimated at 1.4 billion tons grading 17.4% P_2O_5 (18), of which about 500 million tons averaging

19% P_2O_5 were assumed to be demonstrated for this evaluation.

Other deposits in the Georgina Basin are Lady Annie-Lady Jane, D Tree, and a nearly contiguous group of deposits (Babbling Brook Hills, Highland, Mount Jennifer, Mount O'Connor, Phantom Hills, and Riversleigh) referred to as the Northern Deposits. Total demonstrated in situ resources for these deposits is about 950 million tons, of which the largest is Lady Annie-Lady Jane. It contains 486 million tons of in situ resources averaging 17% P_2O_5 (18).

Additional Australian deposits that contain inferred resources include Wonarah in Northern Territory and Sherrin Creek-Lily Creek in Queensland. Together, these deposits contain a total of 422 million tons of recoverable phosphate rock at the inferred level.

A small quantity of phosphate rock is also produced each year from deposits in southern Australia. Due to their minor significance, these deposits were not included in this study.

Nauru

Nauru is a small island in the western Pacific, about 2,700 km northwest of the eastern coast of Australia (fig. 11). It covers an area of 5 km by 4.8 km, with a central plateau 61 m above sea level. The central limestone plateau has been intensely weathered, forming a distinctive karstlike topography. The phosphate occurs in troughs or sinkholes up to 12 m deep. Of the estimated 14.6 km^2 of minable phosphate-bearing land, one-third has been mined out, leaving a total of 25 to 30 million demonstrated in situ tons averaging 38.4% P_2O_5 (19).

SOUTH AMERICA

Brazil

Phosphate occurs in Brazil as igneous apatite, sedimentary phosphorite, aluminum phosphate, and leached guano, with most production from the apatite-rich carbonatite complexes near Sao Paulo in Minas Gerais district. Igneous apatite deposits are both primary, consisting of apatite in intrusive carbonatite plugs, and secondary, the weathered surficial parts of the carbonatite plugs enriched in apatite owing to selective leaching of carbonates. The carbonatite deposits typically contain other important ore minerals, including columbium, vermiculite, titanium minerals, and rare earths.

Jacupiranga is a Lower Cretaceous carbonatite complex located 215 km south of Sao Paulo. The deposit is of the same age and similar nature as other Brazilian igneous basic-alkaline intrusive ore bodies (e.g., Araxa, Tapira) and has a well-defined carbonatite plug. The apatite appears to be confined to the carbonatite, and mining is restricted to that rock type. The complex occurs as a dome-shaped hill over an area of 7 km by 10 km. It has been mined since 1943 with present production from unweathered rock, which constitutes a reported (presumedly demonstrated) in situ reserve of 100 million tons of carbonatite rock averaging 5% P_2O_5 (15).

Phosphate deposits in weathered carbonatite complexes evaluated as part of this study include Anitapolis, Araxa, Catalao, Ipanema, and Tapira (fig. 13). The largest of these in terms of phosphate resources is Tapira, a weathered volcanic chimney with a surface area of 30 km^2, containing demonstrated in situ resources totaling in excess of 800 million tons averaging 8.7% P_2O_5 (15). Besides phosphate, Tapira contains commercial quantities of titanium, rare earths, vermiculite, and columbium. Total demonstrated in situ resources of the deposits listed above are more than 2 billion tons; average grade of the deposits is about 9% P_2O_5.

Deposits of sedimentary origin studied include Itataia, Olinda-Paulista, and Patos de Minas (fig. 13). Itataia is a Precambrian complex of marbles and gneisses exposed in the Rio Curu-Independencia Fold Belt and contains substantial amounts of uranium along with phosphate.

LEGEND

▲ Discrete individual deposits

FIGURE 13. - Location map, South American deposits. *1*, Anitapolis; *2*, Araxa; *3*, Catalao; *4*, Ipanema; *5*, Itataia; *6*, Jacupiranga; *7*, Olinda-Paulista; *8*, Patos de Minas; *9*, Tapira; *10*, Pesca-Conejera-Sardinata; *11*, Bayovar; *12*, Riecito.

Phosphate deposits at Olinda are in the upper Cretaceous Grammame Group associated with marl, limestone, and clay. Although phosphate occurs throughout the Grammame in the Olinda area, the only beds of commercial importance are in the lower part of the sequence. Beds range between 0.2 and 4 m thick, and overall P_2O_5 content averages 20%. In situ reserves at Olinda have been estimated to be between 30 and 50 million tons (15).

The phosphate deposits of Patos de Minas occur as lenses and pods in the late Precambrian-Lower Cambrian Bambui Group, which is a folded and faulted metasedimentary sequence covering most of the western half of Minas Gerais and extending into Goias and Bahia. Phosphate-bearing lenses occur up to 80 m thick over an area of 0.4 km by 3 km. Much of the Bambui has yet to be extensively explored, so it is likely that addiitional deposits will be discovered. Total demonstrated resources as of January 1981 for the Itataia, Olinda, and Patos deposits were 136 million tons of recoverable product.

Demonstrated resources for all Brazilian deposits analyzed total 406 million tons of recoverable product. There are an additional 7 million tons of recoverable product at the inferred level.

Colombia, Peru, and Venezuela

Other than the Brazilian phosphates, the only South American deposits evaluated for this study are at Pesca in Colombia, Bayovar in Peru, and Riecito in Venezuela (fig. 13).

Although there are several reported phosphate occurrences in Colombia, those in the Pesca area are considered the most economically viable and were thus selected for detailed analysis in this study. The Pesca deposits (including Conejera and Sardinata) are located 95 km northeast of Tunja in Boyaca Department. Occurrences of phosphate in Boyaca have been known since 1958, but plans for large-scale development were not formulated until 1974. The deposits are in the bottom part of the Upper Cretaceous Plaeners Formation. The main phosphate bed averages 2.5 m in thickness and is composed of apatite pellets and minor clay cemented by chertlike silica. The Plaeners, which crops out along the northern flank of a mountain and dips 15° to 20° to the south, will have to be mined by underground methods because of 200 m of overburden.

Ore grade in the Pesca and Conejera deposits averages about 20% P_2O_5. Demonstrated in situ resources total 44 million tons, but there are substantially more potentially available in the area, possibly totaling 120 million tons (20). Total demonstrated resources in all three Pesca-Conejera-Sardinata Deposits are about 425 million tons grading 18% P_2O_5.

The Bayovar deposit in the Sechura Desert of Peru is a marine pelletal phosphorite of Miocene age interbedded with diatomite and tuff. The Sechura apatite is a carbonate flurohydroxyapatite low in fluorine and high in CO_3 content. The deposit has been divided into three main ore zones: the Diana in the lower diatomite and phosphate, the Zero, and the Minerva in the upper diatomite and phosphate. The Diana is the richest and thickest of these, averaging 30 to 40 m in thickness, with ore contained in seven beds. Average thickness of the ore-bearing interval is 165 m, with overburden of 120 m. Reserves of rock have been established as being approximately 560 million tons of 30.5% P_2O_5 (15). However, only about 20% of the area has been prospected, and there could be several billion tons of additional resources potentially available. The total demonstrated resource is about 2 billion tons grading about 5% P_2O_5.

Phosphorite in Venezuela is found in Upper Cretaceous sediments, primarily in Tachira State in the Merida Andes and in rocks of lower Miocene age north of Aroa, in Falcon State, where exploitation at the Riecito Mine began in 1956. The mine produces from two phosphate beds in the Pozon Formation, composed of hard, massive siliceous phosphatic breccia consisting of angular quartz fragments cemented by very fine grained apatite. The ore zone averages 9 to 14 m in thickness. The Pozon here has been folded into an asymmetrical anticline transsected by a transverse fault which divides the deposit into two portions. In the mining area, beds dip at 5° to 15°. Overburden thickness averages 21 m. Proven (measured) in situ reserves of high-grade material (27% to 30% P_2O_5) are reported to total 20 million tons (15).

WEST AFRICA

Senegal

There are two phosphate mining operations, Pallo and Taiba (including Tobene), in Senegal, which account for all of that country's annual mineral exports. Locations are shown in figure 14. Both produce phosphate from Eocene rocks in a 200-km-long belt of sediments parallel

FIGURE 14. - Location map, west African deposits. *1*, Pallo; *2*, Taiba; *3*, Hahotoe; *4*, Kpogame.

to the coast. The deposits are largely aluminum calcium phosphates, which are the end product of laterization of the original sedimentary pelletal phosphates. Ore beds average 17 m and 6 m in thickness at Pallo and Taiba, respectively. Overburden depth is 3 m at Pallo and 25 m at Taiba. The two deposits together contain 537 million tons of in situ demonstrated resources averaging 31% P_2O_5, resulting in 130 million tons of recoverable product.

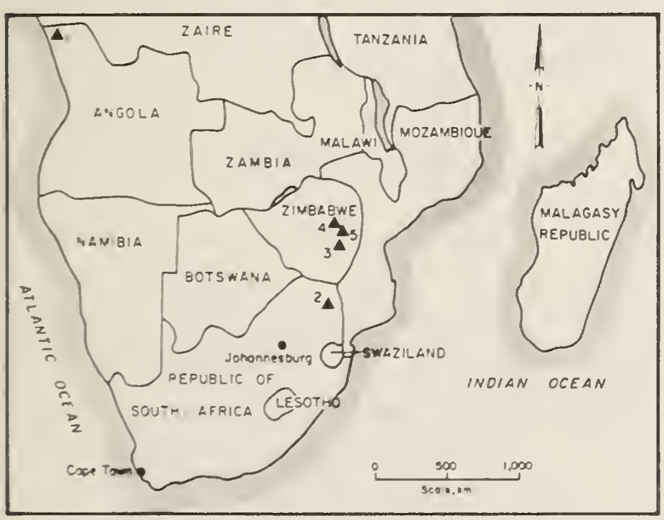
Togo

Although Togo (fig. 14) is a small country of only 57,000 km^2, it is presently the world's third largest exporter of phosphate after the United States and Morocco. Production in 1980 totaled over 2.9 million tons (21). Phosphate occurs as oolitic grains of apatite in Eocene sediments that are confined to a narrow belt 2 km by 35 km in the southern part of the country. Of the five known deposits (Adeta, Kpogame, Hahotoe, Dagbati, and Mome), only Hahotoe and Kpogame are in production. They were the only deposits evaluated containing resources at the demonstrated level, a total of about 100 million tons in situ (22) at a grade of 30% P_2O_5. Dagbati has an estimated 29 million tons of recoverable phosphate rock at the inferred level. There are generally two phosphate beds, ranging between 2 and 6 m in thickness and separated by a layer of phosphatic marl. Thickness of the overburden of sand and clay averages 15 m.

SOUTHERN AFRICA

Three deposits in southern Africa were evaluated as part of this study. They are Lacunga River in Angola, Palabora in the Republic of South Africa, and Dorowa in Zimbabwe. Lacunga River is of sedimentary origin, and the others are igneous apatites. All are shown in figure 15.

The Lacunga River deposits were first identified in 1951 and are located near the coast and 100 km south of the Congo River in the Zaire District. The deposits consist of unconsolidated phosphate pebbles, phosphatic coprolites, and quartz sands of lower Eocene age. The ore zone averages less than 1 m in thickness, overlain by 2 m of overburden. In situ resources, assumed to be demonstrated for this study, have been estimated at 27.5 million tons averaging 19% P_2O_5 (15).



LEGEND

▲ Discrete individual deposits

FIGURE 15. - Location map, southern African deposits. *1*, Lacunga River; *2*, Palabora; *3*, Chishonya (inferred only); *4*, Dorowa; *5*, Shawa (inferred only).

The igneous apatites at Palabora are by far the most important phosphate resource in all of southern Africa. Palabora is located in the northeast Transvaal Low Veld and occupies an outcrop area of 20 km^2. It is essentially a large body of pyroxenite ringed by syenite and intruded into Precambrian granites. The pyroxenite encloses a plug of carbonatite which has been intruded into the center of the complex. The carbonatite is composed of crystalline dolomitic calcite along with varying amounts of magnetite, apatite, and serpentinized olivine. There are basically two apatite deposits, a relatively high-grade band of foskorite surrounding the carbonatite core, and disseminated apatite in the pyroxenites. Based on a 1,000-m depth, there are estimated to be 21.6 billion tons of demonstrated in situ resources of 6.7% P_2O_5. There are inferred to be an additional 10.8 billion tons between a depth of 1,000 and 1,500 m (23).

Three potential phosphate sources occur in the valley of the Sabi River in eastern Zimbabwe. All are carbonatite complexes located at Dorowa, Shawa, and Chishanya. Dorowa is the only one being exploited at this time and is the only Zimbabwean deposit evaluated for this study. It is a circular plug of serpentinized dunite, 6 km in diameter, enclosed by a zone of syenitic fenite which grades outward into the Precambrian granite country rock. A ring dike of dolomitic carbonate has been intruded into the central core of the dunite plug about 800 m from its center. Apatite is present as an accessory mineral in ijolite, carbonatite, and certain fenites. Minable resources have been established at 18 million tons 2.6% to 4.9% P_2O_5.

ASIA

Two Asian deposits were considered for this study: the Jhamarkotra Mine in the State of Rajasthan, India, and Hazara

(Lagardon and Kakul) in the foothills of the Himalayas, Pakistan. Only the Jhamarkotra Mine was evaluated.

Jhamarkotra is considered to be the only phosphate deposit of major significance in India, although there are several other deposits of both sedimentary and igneous (carbonatite) origin in the country. The deposits at Jhamarkotra are Precambrian metasediments of the Aravilli Group, which crop out at or near the tops and on the slopes of a series of low hills. The phosphatic unit dips at an angle of 30° to 60° and is traceable over about 20 km. Individual mineralized zones are typically lenticular in shape and range up to 11 m in thickness, averaging about 6 m. Average overburden thickness is 24 m.

Proven reserves of rock at Jhamarkotra are estimated to be 63 million tons, of which 17 million tons are relatively high grade, averaging 30% P_2O_5. The remainder averages about 18% to 20% (24). The deposit has been exploited since 1969, with initial production from the high-grade portion.

The Kakul and Lagardon deposits, collectively referred to as the Hazara deposit, are located in the Hazara District of the Northwest Frontier Province of Pakistan, where phosphate deposits where first discovered in 1970. Phosphates occur within the upper cherty dolomitic unit of the Lower Cambrian Abbottabad Formation. The deposit is a steeply dipping (about 70°) tabular body averaging 2 m in thickness. Principal phosphate minerals are dahlite and francolite. There are proven reserves of about 14.5 million tons of rock averaging about 28% P_2O_5 at Hazara (25). Apparently, only pilot-plant-phase mining has occurred at Kakul, but production was scheduled for 1982 (26). Mining has never been reported from Lagardon.

Two small producing Indian deposits (Jhabua and Mussoorie) containing 11 million tons grading 28% P_2O_5 and a large deposit in Vietnam (Lao Cay) with 1 billion tons averaging 26% P_2O_5 were not included in this evaluation primarily owing to a lack of information on them.

EUROPE

The only European deposits evaluated for this study are two carbonatite complexes in Finland, Siilinjärvi and Sokli. Siilinjärvi is located in east-central Finland 20 km north of Kuopio, and Sokli is in Lapland (fig. 16). The nearest village to Sokli is Savukoski, 90 km to the southwest. Total demonstrated recoverable rock contained in both deposits is 115 million tons.

LEGEND

▲ **Discrete individual deposits**

FIGURE 16. - Location map, U.S.S.R. and Finland deposits. *1*, Chilisay; *2*, Kara Tau; *3*, Kingisepp; *4*, Kola Combine; *5*, Kovdor; *6*, Viatka-Kama; *7*, Yegorievsk-Lopatino (inferred only); *8*, Siilinjärvi; *9*, Sokli.

The Siilinjärvi complex, discovered in 1954, is a vertical, tabular body 16 km long and up to 1.5 km wide. It is Precambrian in age, one of the oldest carbonatite complexes known, and intrudes a granitic gneiss. The main constituents are 65% phlogopite mica, 22% carbonate, and 10% fluorapatite. Grades are generally uniform laterally and vertically. Demonstrated in situ reserves are estimated to be 465 million tons averaging 4.15% P_2O_5 to 100 m depth (15); however, the ore zone has been drilled to at least 800 m, and the total demonstrated resource is nearly 1 billion tons. Overburden thickness averages only 5 m and consists of unconsolidated glacial material.

The Sokli deposit, discovered in the 1960's, is a large circular intrusive 5 km in diameter, grading 2% to 4% P_2O_5. The phosphate-bearing zone ranges from 0 to 80 m in thickness, averaging 25 m. Overburden consists of 1 to 15 m of unconsolidated glacial material. The 3.3-km^2 area being evaluated by Rautaruukkii Oy (deposit owner) for initial exploitation has been enriched by weathering to over 15% P_2O_5. In situ reserves have been reported at about 100 million tons averaging about 17% P_2O_5 (15). Based on information obtained for this evaluation, demonstrated in situ resources have been estimated to total about 140 million tons at 18% P_2O_5.

CENTRALLY PLANNED ECONOMY COUNTRIES

U.S.S.R.

The U.S.S.R. is the world's second largest producer of phosphate, with 1981 production estimated at 26 million tons of phosphate rock (revised estimate from the 30,950,000 tons reported by the Bureau of Mines in the past). The majority of Soviet production comes from the apatite deposits of the Kola Peninsula, and the remainder from several deposits, most of sedimentary origin, throughout European Russia (fig. 16). Phosphate-bearing deposits evaluated include the Kola Combine, Kovdor, Kara Tau, Kingisepp, Kovdor, Oshurkovo (in the eastern U.S.S.R.), Viatka-Kama, and Chilisay. Total demonstrated recoverable phosphate rock in Soviet deposits studied is 1,333 million tons. This represents only a portion of the U.S.S.R.'s resources, which are much larger.

The Kola deposits were discovered in 1929, and production began shortly thereafter. They occur in the Khibiny Pluton, a middle to upper Paleozoic series of nepheline-syenite intrusions about 40 km in diameter. The apatite-rich rocks occur within a band of ijolitic rocks surrounding the pluton core. Phosphate-bearing layers range from 10 m to over 200 m in thickness. Ore grade varies, with currently produced ore averaging about 16.5% P_2O_5. Demonstrated in situ resources are estimated to be about 1.8 billion tons.

Kovdor (also on the Kola Peninsula) is an alkalic, ultrabasic igneous complex of middle Devonian age, occupying an area of 38 km^2, located 150 km southwest of Murmansk. Apatite-rich rocks occur in nearly vertical lenses and veins of variable thickness. The deposit has been open-pit-mined for magnetite since 1964. Apatite has been recovered since 1974 from the tailings of the magnetite mining. Feedstock to the phosphate recovery mill averages about 10% P_2O_5. In situ resources, assumed to be demonstrated for this study, were estimated to be 113 million tons at an average grade of 6.6% P_2O_5 (27).

The Kara Tau complex consists of more than 40 separate deposits distributed over an area of 120 by 25 km along the northern slope of the Karatau mountain range, about 120 km north of Chimkent. Mining began in 1942 as a small surface operation. Production is from Lower Cambrian sediments, with the primary phosphorite bed about 5 m to 12 m thick. Average P_2O_5 content at Dzhanatas, largest of the deposits, is 25.6% (15). Total minable phosphorite resources in all deposits were estimated to be 1.5 billion tons, of which more than half is contained in the five largest deposits (28). These resources were assumed to be demonstrated for purposes of this study.

Kingisepp consists of three mines (Maardu, Toolse, and Kingisepp) producing from Lower Ordovician arenaceous schists bearing phosphatic shells. The deposit is located 125 km southwest of Leningrad near the Gulf of Finland. The ore averages 6% P_2O_5, with an estimated 230 million in situ tons present (15).

The Oshurkovo deposit occurs within a strongly metamorphosed biotite-hornblende diorite complex located east of the southern end of Lake Baykal and 15 km northwest of Ulan-Ude. Although located in a remote region of the country and not represented on figure 16, the deposit is close to the Trans-Siberian railway. The minable deposits consist of steeply dipping rocks covering an area of 3.5 km^2. Phosphate-bearing rock is present at the surface and extends to a known depth of 100 m. There is a total of 870 million tons demonstrated resources in situ, averaging 4% to 5% P_2O_5 (15). Development of this deposit is planned.

The Chilisay phosphorites are located at the southern end of the Urals near the city of Aktyubinsk, 500 km northeast of the Caspian Sea. Deposits in the region have been known and exploited locally since 1929, but two major mining units should become operational within the next few years. Production is from two sedimentary beds of Upper Cretaceous age ranging in thickness between 0.2 m and 0.85 m. Overburden thickness is minimal, averaging about 10 m. Ore grade at Chilisay averages 10% P_2O_5 on an in situ demonstrated resource that has been estimated to be 269 million tons. Total in situ resources in the region are reportedly about 1 billion tons. Apparently the concentrate is used for direct application because the magnesium content may prohibit its use for acid production (15).

The Viatka-Kama deposits, discovered in 1917, occur within the largest known sedimentary sequence in European Russia. The mine is located about 150 km northeast of Kirov. Phosphate occurs as a 1-m-thick layer of phosphorite nodules in glauconitic sand of Lower Cretaceous age. Ore grade averages 12% to 14% P_2O_5, and there is an estimated 1 billion tons of in situ demonstrated resources (15).

Other significant Soviet deposits not analyzed in detail for this analysis, owing to a lack of sufficient data, include Seligdar and Yegorievsk-Lopatino. Seligdar is located in Yakutia, 50 km north of Aldan. It is of igneous origin, pipelike in shape, covering an area of 2.4 km^2. The ore body is essentially a dolomitic carbonatite, averaging 6% to 6.5% P_2O_5 but ranging between 2% and 40%. British Sulphur (15) reported resources to be 3 billion tons of apatite. A feasibility study for development at Seligdar was scheduled for completion in 1979.

Yegorievsk and Lopatino are two active mines located 90 km southwest of Moscow. The deposits occur as outcrops of phosphatic, glauconitic sands, and clays of Upper Jurassic and Lower Cretaceous age. Total resources are not known, but the grade at Yegorievsk is reported to range between 7% and 14% P_2O_5 in two phosphatic horizons (15).

China

Information concerning the phosphate resources and geology of China is limited, but there are known to be mining operations in deposits throughout the country. Total Chinese production averages about 12 million tons of phosphate rock and apatite annually.

All of the Chinese deposits considered for this study are either producing or in development stages. Deposits studied include Jingshan,[9] Zhongxiang, Gaiyang, Kunming, Jinning, Shandong Province,

[9]All names are in Pinyin.

Jingbing, Jin He, Fanshan, Fuchuan, and Emei (fig. 17). Except for Shandong Province, which includes about 400 individual mines, all are, or presumably would be, discrete operations. Total demonstrated resources contained in the deposits are 208 million tons of recoverable phosphate rock.

Gaiyang is believed to be the largest single phosphate mine in China. It is located 45 km north of the town of Gaiyang in Guizhou Province. Phosphate is mined from steeply inclined beds near the base of the Precambrian Doushanto Formation, which consists of shales and phosphatic layers in the lower portion, with dolomitic marls predominant near the top. P_2O_5 grade of minable units averages 30% to 35%. Demonstrated resources of rock are estimated to total at least 20 million tons, based on an assumed 14-year mine life remaining at current production levels.

LEGEND

▲ Discrete individual deposits

FIGURE 17. - Location map, Chinese deposits. *1*, Emei (inferred only); *2*, Fanshan (inferred only); *3*, Fuchuan and Gaiyang; *4*, Kunming and Jinning; *5*, Jingbing (inferred only); *6*, Jingshan; *7*, Jin He (inferred only); *8*, Shandong; *9*, Zhangxiang.

Eighty kilometers east of Gaiyang is the Fuchuan deposit, discovered in 1976 and presently in a developing stage. It is probably within the Doushanto Formation. Fuchuan resources are apparently very extensive, possibly 800 to 900 million in situ tons at 25% to 30% P_2O_5.

Other major producing deposits located within the Doushanto Formation occur at Jingshan and Zhongxiang, in Hubei Province, 110 km northwest and 175 km west-northwest, respectively, of Wuhan. Exploitation began at both in the 1960's. Production is from the lowest of four phosphatic horizons occurring within a sequence of interbedded dolomites and dolomitic marls. The minable bed is 1 to 2 m thick, and the Doushanto Formation here reaches a total thickness of 300 m. Assuming a 14-year life remaining and present production levels, there are assumed to be at least 4.2 million tons of demonstrated rock resources at Jingshan and 5.8 million tons at Zhongxiang. Grade has been reported at 28% to 35% P_2O_5 (15).

Other important Chinese production occurs at Jinning in central Yunnan Province, 40 km south-southeast of the city of Kunming. Exploitation began there about 1966 from two massive beds within the Lower Cambrian Meisuchen Formation, a member of the Lei-Bo suite which contains phosphatic units in other areas of China. The beds are exposed on the south side of an east-west anticline and dip to the south at 15°. Ten kilometers north of the Jinning Mine, on the north limb of the anticline, is the Kunming deposit. Beds on the north limb dip at 3° to 8°. At both Kunming and Jinning, there are two ore beds, the lower of which is 3 to 6 m thick, separated from the upper by 10 m of dolomite. The upper bed averages between 8 and 10 m in thickness and is of slightly higher grade than the lower. Average grade of total proven ore is 25% P_2O_5. Fluorapatite is the ore mineral, with minor amounts of magnesium oxide and greater than 2% fluorine. Measured reserves at each deposit are 65 million tons in situ (9), but apparently there are several hundred million tons of additional resources in the area that have yet to be defined. Li and Wang (30) stated that the two deposits could account for 70% of China's rock production for the foreseeable future.

Shandong Province in northeastern China contains deposits of igneous apatite. Little is known about the deposits, except that a grade of 28% P_2O_5 suggests that enrichment through weathering has occurred and the ore lies near the surface. The deposits, containing an estimated 150 million tons in situ demonstrated resources (15), are exploited by as many as 400 individual mining operations.

The only other known igneous apatite deposit occurs 36 km southwest of Beijing. It is believed to be of Precambrian age, was discovered in 1977, and is referred to as the Fanshan deposit. It has been described as the largest deposit in northern China (31), but no resource data are given. Development of the deposit would provide a local source of phosphate, which would preclude having to transport rock from Yunnan and Guizhou, over 1,800 km to the southwest.

The Jingbing, Jin He, and Emei deposits in Sichuan Province comprise an extensive phosphate resource, but figures are unavailable. Jingbing is located 340 km southwest of Chongqing in the southeastern part of the Province, while Jin He and Emei are 180 km south-southwest and 275 km west, respectively, of Chonqing, in central Sichuan. All are believed to occur within the Lower Cambrian Lei-Bo suite, which contains the phosphate currently mined at Kunyang, several hundred kilometers to the south in Yunnan Province. The suite is 30 to 50 m thick at Emei, where it is exposed. The phosphatic horizon is 5 m thick and occurs within interbedded dolomites and cherts.

MINING AND PROCESSING OF PHOSPHATE

MINING METHODS

Nearly 88% of the phosphate rock product produced in market economy countries today is recovered by surface mining methods. The remaining 12% is recovered by underground mining techniques, predominantly in Morocco and Tunisia. In the U.S.S.R. and China, approximately 30% and 23%, respectively, of the phosphate rock product is recovered by underground mining methods. Appendix B shows specific deposit data such as mining and milling methods, status, capacities, grades, deposit type, ownership, and initial year of production for the deposits and mines included in this study.

Surface

The two major surface-mining methods used in the phosphate industry are strip mining and open pit mining. A third method, dredging, is used in special situations. Strip mining accounts for 90% of U.S. and 57% of total world phosphate rock production. Market economy country production by this method is almost 72%. Strip mining is predominantly used because of the tabular, bedded, sedimentary nature of most phosphate deposits. Most deposits in the Southeastern United States and North Africa use this method.

Nearly 16% of current market economy country phosphate rock production is supplied by the open pit mining method. Open pit mining is extensively employed to exploit the massive igneous phosphate carbonatites, which in themselves contribute approximately 5% to current market economy country production of phosphate rock. The U.S.S.R. and China derive 69% and 32% of their respective production from igneous sources. Dredging is employed at a few deposits throughout the world, particularly at the Wingate Creek operation in Florida (U.S.), and will be employed at the proposed Santo Domingo operation in Mexico. It is also used to strip off overburden at Texasgulf's Lee Creek Mine in North Carolina (U.S.).

Strip Level

An estimated 75% of the mines producing at the time of this study are using the strip level mining method. Approximately 82% of those not producing would probably use this method of mining.

In this method the overburden is stripped from an initial cut and stockpiled. The phosphate ore is excavated while a second parallel cut is being stripped of overburden. The waste from the second cut is side-cast into the first cut. This cycle is repeated as the mining proceeds.

In the larger operations, overburden is stripped by draglines or bucket-wheel excavators and cast into the adjacent mined-out strip. In smaller operations, or where selective mining is critical, scrapers and bulldozers with rippers working in tandem are used, with the waste material being dumped into the previous strip. Some strip mine operations utilize dredges to remove a portion of the overburden. An example of this is the Lee Creek operation in North Carolina.

Ore removal is accomplished by a dragline, scraper, or shovel-truck operation. In Florida, draglines dump the ore into a slurry pit where the phosphate material is slurried and pumped through pipes to the beneficiation plant. Most phosphate ore or overburden requires little or no drilling or blasting prior to excavation. The strip level method is used extensively in the Southeastern United States and North Africa; blasting is frequently required to mine Moroccan deposits.

Open Pit

Open pit mining is employed to recover hard igneous carbonatite rock. The method differs from strip mining in that the waste is stored separately instead of being dumped into mined-out areas. Benching of the waste and ore is often necessary owing to the thickness or depth of the ore.

Overburden removal is accomplished by shovel, front-end loader, or dragline in conjunction with trucks. In some cases, scrapers and bulldozers working in tandem are used to excavate and transport the waste to the dump.

The same equipment and methods are used to mine the ore as are used for overburden removal. Drilling and blasting are more common in open pit mining than in strip mining. This is due to the harder nature of the carbonatite deposits that this method is suited for.

Dredging

This method is used in special hydrologic situations for which the overburden and phosphate horizon are unconsolidated clay and sand. Salardina Bay in South Africa mines phosphate using dredges. Texasgulf Chemicals Co., North Carolina, uses a dredge to remove overburden. Pumps dewater the pit, and draglines mine the ore from a bench.

Underground

The relatively low unit value of phosphate rock makes underground mining methods generally unprofitable. However, steeply dipping phosphate beds or high stripping ratios sometimes make the use of underground mining techniques preferable. In such cases, highly mechanized room-and-pillar, longwall caving, and overhand-stoping methods have been used successfully. While only 12% of present phosphate rock production capacity in market economy countries is from underground methods, this study estimates that 18% of the capacity of deposits not producing at the time of the study could be from underground mines. The majority of producing underground phosphate mines are located in north Africa.

Room and Pillar

A horizontal- to shallow-dipping phosphate bed, with fairly competent strata overlying the ore zone is necessary for successful room-and-pillar mining. This method consists of interconnecting openings with pillars left for roof support. Access is usually from the outcrop or pit wall but may be by incline or vertical shaft. Continuous mining machines similar to those used in coal and potash mining are used to excavate the phosphate ore. Sometimes drilling and blasting are required, with slushers or front-end loaders used to load the broken ore. Trucks or conveyors transport the ore to the surface.

Approximately 9% of current market economy country phosphate rock product capacity is supplied by room-and-pillar mining operations. Morocco and Tunisia contribute over 90% of this room-and-pillar capacity. Future projections indicate nearly 8% of the capacity from nonproducing deposits in market economy countries could be from room-and-pillar operations.

Overhand Stoping

Steeply dipping beds or massive ore bodies, such as the igneous carbonatites, can be mined by overhand-stoping methods. Various methods fall under the category of overhand stoping, such as cut-and-fill and shrinkage stoping. The material is first drilled and blasted, then loaded with slushers or load-haul-dump machines. Transportation to the surface is by either rail, truck, or load-haul-dump. Loading in the shrinkage-stoping method is usually from ore chutes that draw broken ore from the stope into trucks or rail cars. Overhand stoping is not being used in any of the producing properties in market economy countries included in the study. The U.S.S.R. and China use overhand-stoping methods for all current underground mining. This represents 37% of the phosphate rock production capacity in these countries. Nearly 10% of the estimated new capacity in the United States from developing and explored deposits could be supplied by this method. Wyoming is the principal location for the proposed application of overhand stoping in this country.

Longwall Caving

Longwall caving is a highly productive but capital intensive mining method used in flat-lying bedded deposits of coal, potash, and phosphate. The ore is cut from a long face, usually greater than 50 m in length, by a cutting drum, also called a face shear. The broken ore drops onto a conveyor belt that runs parallel to the face and is transported to the surface. Roof support chocks keep the roof from caving in at the face to allow working room for the men and equipment. As the face advances, the roof support chocks and conveyor are advanced, allowing the roof to cave in behind.

Only two producing mines, Recette No. 7 (Youssoufia Black Rock) in Morocco and the Sehib Mine in Tunisia, use this method. This represents 3% of market economy countries' existing capacity, or almost 20% of existing phosphate rock production capacity in north Africa.

BENEFICIATION METHODS

In almost all cases the run-of-mine phosphate material has to be beneficiated. The basic beneficiation methods employed in the phosphate industry are sizing, washing, flotation, calcining, and calcining with leaching. A phosphate beneficiation plant may use one or more of these methods to produce a marketable product.

The milling method assigned to properties in this study indicates the most significant method used to beneficiate the phosphate material. An example would be a property that screens and washes before sending the phosphate material through a flotation circuit. The milling method for this property would be listed as flotation, even though sizing and washing were used.

In the United States, 87% of current phosphate rock product capacity is beneficiated through flotation, followed by calcining and washing at 9% and 4%,

TABLE 4. - Phosphate mill plant operating parameters, by region[1]

Region	Producing mines			Nonproducing deposits		
	Feed grade, % P_2O_5	Product grade, % P_2O_5	Recovery, %	Feed grade, % P_2O_5	Product grade, % P_2O_5	Recovery, %
United States:						
Southeast	8.4	31.7	89.6	5.7	30.7	85.1
West	25.2	30.6	80.1	21.9	28.4	79.2
South America	10.3	35.2	61.7	10.8	32.3	68.7
North Africa	29.5	31.5	62.3	29.6	33.2	65.8
Middle East and Asia	26.4	32.3	66.7	24.5	31.4	67.9
Oceania, including Australia	36.1	37.2	83.7	17.3	34.1	83.4

[1]Feed grade, product grade, and recovery are weighted average for all the deposits in each region.

respectively. An estimated 48% of current world production is beneficiated through flotation, followed by washing--34%, siz-ing--14%, and calcining--6%.

Average feed grade, average product grade, and average mill recovery are shown in table 4 for the various market economy country regions. Feed grade is here defined as the recoverable grade of the ore that feeds the mill. As shown in this table, the Southeastern United States has the lowest average feed grade but the highest average recovery (at 8.4% P_2O_5 and 89.6%, respectively). North Africa, on the other hand, has an average feed grade of 29.5% P_2O_5 but a mill recovery of only 62.3% owing to losses of fine material during washing.

Sizing

Sizing is primarily used on direct-shipping material that already meets acid plant chemical specifications. Oversized waste material, such as limestone and dolomite, is removed by screening, and the phosphate ore is crushed and sometimes ground to meet acid plant size specifications.

Washing

The purpose of washing is to remove the minus 150-mesh clay-sized slimes fraction from the run-of-mine material. The clay-sized fraction contains impurities such as aluminum which cause high reagent consumption in the flotation circuit and acid consumption in the phosphoric acid plant. The largest loss of phosphate occurs in the washing process.

Screening is typically used to remove the larger limestone and dolomite gangue material prior to desliming. In Florida the screen oversize (plus 14 mesh) is washed to remove clay particles and rescreened at 0.75 in to reject limestone

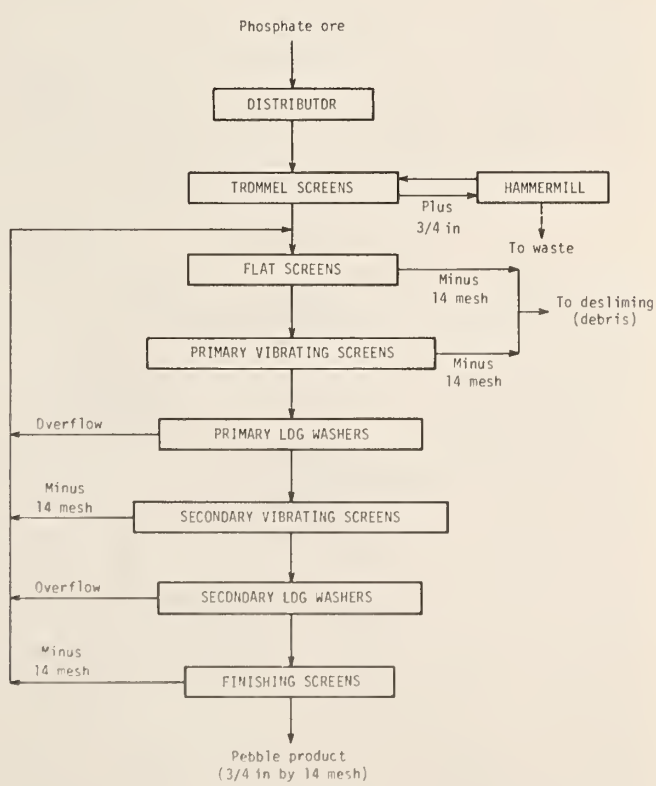


FIGURE 18. - Typical Florida phosphate washing circuit.

gangue. The intermediate minus 0.75-in, plus 14-mesh pebble fraction is shipped directly to the acid plant (fig. 18).

In the desliming section of the washing plant, the clay-sized particles are removed from the screen undersize fraction with cyclones. The minus 150-mesh slimes are pumped or flow to the waste clay pond. The deslimed material is either dried and shipped as a final product or sent to further processing for upgrading.

Flotation

The primary function of flotation is to separate the phosphate minerals from the associated quartz sand or carbonate. The phosphate grade is increased to marketable levels, and the silica and carbonate are reduced to acceptable levels for acid plant feed specifications (fig. 19).

Anionic froth flotation is used in the rougher circuit to float fine phosphate (minus 35 mesh). The cationic froth flotation is used in the cleaner circuit to remove quartz from the phosphate.

The anionic collectors used for phosphate flotation are fatty acids which include crude tall oil, blends of fatty acids, and soap skimmings. The cationic collectors used for silica flotation include tallow amines and condensed amines.

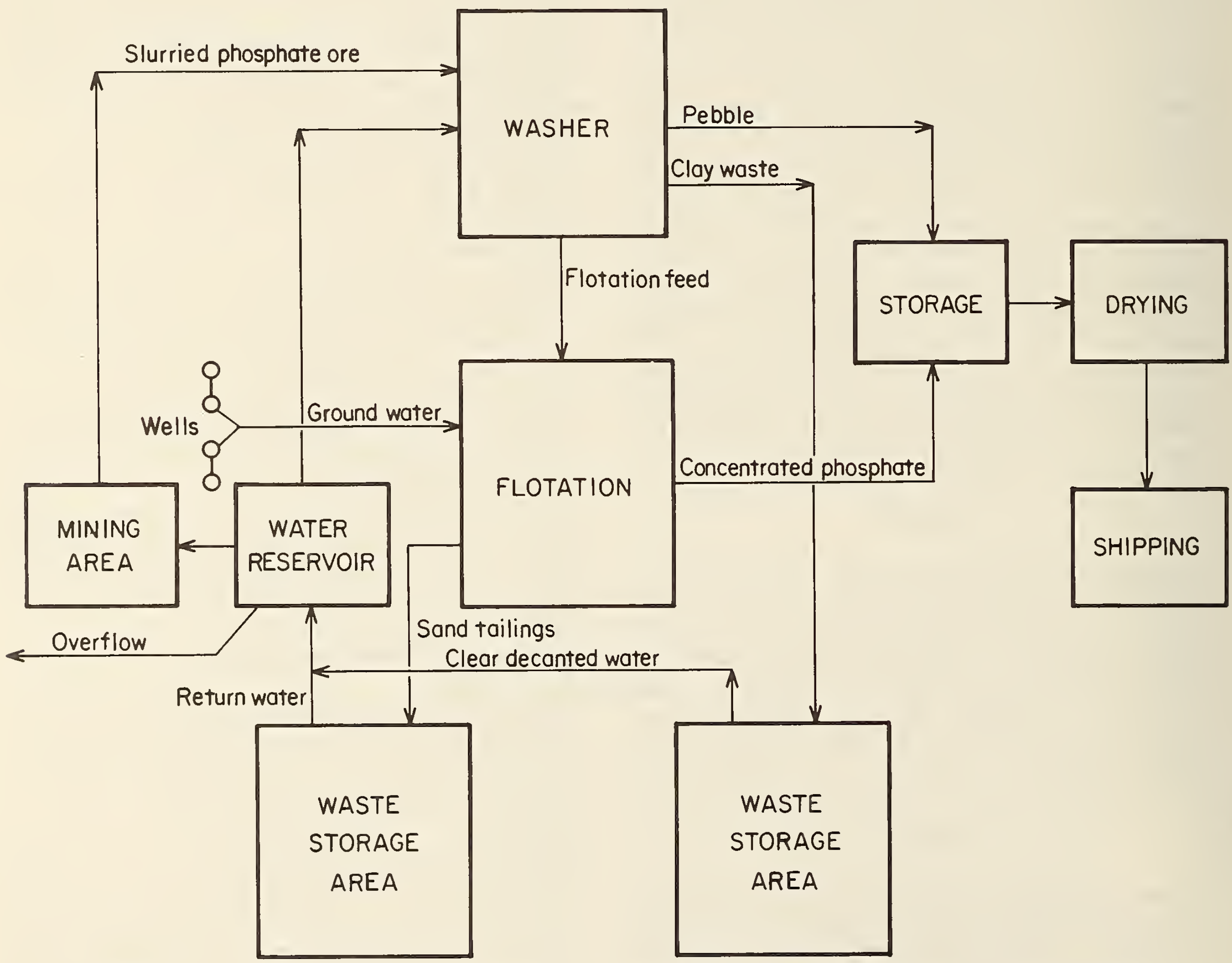


FIGURE 19. - Typical process flowsheet, Southeastern United States, incorporating flotation process.

In some cases, the coarser phosphate (plus 35, minus 14 mesh) requires the use of skin flotation.

Calcining

High levels of organic matter in phosphate rock feed to an acid plant cause excess foaming and darken the acid color. Even after washing and desliming, unacceptable levels of organics may still remain. Calcining is used to remove the organic matter by heating the ore in a fluidized-bed calciner to 800° C or higher (fig. 20).

Drying

To reduce long distance transportation costs, it is important to remove as much water as possible from the phosphate rock by drying. Phosphate rock also must be dried if the grinding circuit is designed for dry rock. Many grinding and phosphoric acid plants will now accept wet rock. Either rotary dyers or fluidized-bed dryers are used to dry the rock. The dry rock is stored in silos or bins until shipped.

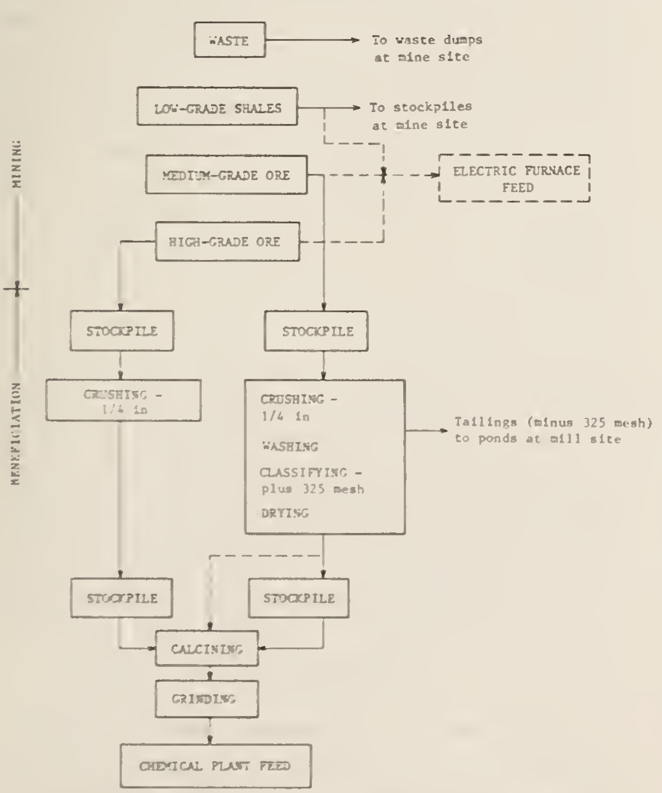


FIGURE 20. - Typical process flowsheet, Western United States, incorporating calcining process.

BYPRODUCTS

Phosphate rock contains several materials that, in most cases, are either very expensive to extract as marketable byproducts or are considered a waste product with little or no market value. The most significant of these potential byproducts are uranium (U_3O_8), recovered from phosphoric acid, vanadium (V_2O_5), removed from ferrophosphorus, and fluorine (F). Gypsum ($CaSO_4 \cdot 2H_2O$) is a waste product from the production of phosphoric acid. Few world operations are recovering any byproducts from phosphate rock. This study only considered byproducts at operations in which the recovery of that commodity significantly impacted upon the economics. The following is a discussion of each byproduct's present extraction process, the potential uses for the byproduct, and the constraints presently inhibiting their recovery.

Uranium is the most important byproduct (or potential byproduct) of phosphate. Most phosphate rock contains uranium, although not in quantities high enough for economic extraction. On the average, approximately 1 ton of 100% P_2O_5 phosphoric acid will produce 1 lb of recoverable U_3O_8 (1).

The extraction of uranium from phosphoric acid is technologically very complex and is not fully comparable to the extraction of uranium from other kinds of ores. There are three basic steps in the recovery of uranium from phosphoric acid. First, the uranium compounds are dissolved with sulfuric acid at the same time that the phosphate rock is digested. Next, the uranium is removed from the phosphoric acid through a new and technically complex solvent extraction process. An important key to the solvent extraction process is the removal of both impurities and organic materials from the acid before solvent extraction of the U_3O_8. These contaminants affect the efficiency and subsequently the economics of the solvent extraction process. The final step in the recovery of uranium is concentrating the separated uranium by precipitating it out of solution to its most common form, the hydrated peroxide salt known as "yellow cake." At this point, the uranium product is in a form suitable for further upgrading through standard uranium refining techniques so that it can be used as fuel for nuclear reactors as well as other uses (1).

Although some phosphoric acid producers are presently recovering the uranium (particularly in the Southeastern United States), extensive research is presently underway to make this process more economical.

Ferrophosphorus is produced as a by-product in the production of elemental phosphorus. Ferrophosphorus collected in the electric furnace contains vanadium as well as other metal impurities. It is often sold for the purpose of extracting vanadium pentoxide. The supply of ferrophosphorus is greater than the demand from vanadium recovery plants (1).

The fluorine content in phosphate rock averages between 3% and 4%. No concentration of fluorine occurs during production of phosphoric acid. Some fluorine is retained in the gypsum waste, some escapes as a gas, and some remains in the acid. The fluorine gas fraction that is recovered as fluosilicic acid represents only about 35% of that which was in the rock prior to phosphoric acid production. The process to recover the fluosilicic acid consists of scrubbing the fluorine gas released when phosphate rock is digested and weak phosphoric acid is heated and concentrated to a higher phosphate content. The principal uses for fluosilicic acid are for water fluoridation and the production of cryolite. This process to recover fluosilicic acid is presently being used by a number of U.S. phosphoric acid producers (1).

Phosphogypsum is a waste byproduct from the wet phosphoric acid process. It is precipitated when the phosphate rock is digested with sulfuric acid. Gypsum is normally stockpiled at the acid plants, with a small percentage used as fertilizer or as a soil conditioner (land plaster). In the United States, phosphogypsum is not presently competitive for use in construction material nor is it an economical source for sulfur (1).

There are a number of other less significant byproducts presently or potentially recoverable from phosphate deposits. These include copper, zircon, precious metals, and vermiculite at the Foskor operation in South Africa, titanium, columbium, rare earths, and vermiculite from Brazilian operations, and montmorillonite from the Thies Mine in Senegal.

PHOSPHATE DEPOSIT COSTS

COSTING METHODOLOGY

The costs used in this study were collected or developed using various methodologies. Costs for the deposits in the Southeastern United States (including Florida, North Carolina, and Tennessee) were developed by the former Bureau of Mines Eastern Field Operations Center in Pittsburgh, PA, in conjunction with Zellars-Williams, Inc. A more detailed discussion and breakdown of these costs and the models used to develop them are available in a Bureau of Mines report entitled "Phosphate Rock Availability--Domestic, A Minerals Availability Program Appraisal" (6). Costs for the deposits in the Western United States (Idaho, Montana, Utah, and Wyoming) were developed by Bureau of Mines Field Operations Centers in Denver, CO, and Spokane, WA, using various methodologies such as scaling from known values, the MAS Cost Estimating System (CES) (32), and actual reported company data. The costs from all the other world countries were collected or developed by Zellars-Williams, Inc., under a contract with the Bureau of

Mines. Some of the foreign deposit costs are actual company reported data, although in most cases they were developed using the contractor's computerized cost model. This cost model uses data on labor, equipment, and supplies that are site specific for each deposit. An estimate was made for the input quantities for these variables, and then a unit cost was assigned for each variable. The unit costs were based on local rates at that deposit converted to 1981 U.S. dollars. The final product of this model is a unit cost for each portion of the mining-milling operation.

Capital expenditures were calculated for exploration, acquisition, development, mine plant and equipment, and constructing and equipping the mill plant, all in U.S. dollars. Capital expenditures for mining and processing facilities include the costs of mobile and stationary equipment, construction, engineering, facilities and utilities, and working capital. A broad category, facilities and utilities (infrastructure), includes the cost of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required for such operating expenses as labor, supplies, taxes, and insurance.

Mine and mill operating costs were also calculated for each deposit, in U.S. dollars. The total operating cost is a combination of direct and indirect costs. Direct operating costs include materials, utilities, direct and maintenance labor, and payroll overhead. Indirect operating costs include technical and clerical labor, administrative costs, facilities maintenance and supplies, and research. Fixed charges, which mainly include local taxes and insurance, are also included in the mine and mill operating costs.

PRODUCTION COSTS

Table 5 and figure 21 illustrate the average costs for selected surface operations included in this study (expressed in January 1981 U.S. dollars per ton of product). In most cases, the mine operating cost for surface deposits is $7 to $13 and mill operating costs is $8 to $14. A few areas in the world deviate from these ranges, particularly the mill operating cost in Morocco, where beneficiation merely consists of screening and drying the ore, and in South America, where the mill operating cost reflects the high cost of beneficiating the carbonatite ore of Brazil. Mining and milling costs for nonproducers are generally greater than those for producers; this is due to the fact for most of the nonproducing deposits, grades are lower and stripping ratios tend to be higher, causing greater costs. The column labeled "Other" primarily includes estimated tax payments. These costs are also greater for nonproducers, because in most cases the overall total costs and revenues necessary to cover them are greater. Transportation costs from mine to plant or port are in most cases small except in the Western United States where the rock in Utah and Wyoming is assumed to go to Idaho and in Australia where the deposits are in the middle of Queensland and the rock must be transported to the coast.

Table 6 and figure 22 illustrate production costs for underground mines and deposits, mainly representing the producers in north Africa and the nonproducers in the United States (Utah and Wyoming). When comparing this table to the previous one on surface mines, it is apparent, as would be expected, that the underground mines are much more expensive to operate. In the case of the north African underground mines, even though they are more expensive to operate than the surface mines, they are near enough to a market that they would still be economical. The underground deposits in the Western United States (particularly the nonproducers in Utah and Wyoming) have costs much higher than any of the other evaluated phosphate deposits in the world. This is largely due to the characteristics of the ore, coupled with the higher costs of underground mining. These highly uneconomical deposits are not likely to be developed in the near future.

TABLE 5. - Production costs for selected world phosphate surface mines and deposits

(All costs are expressed as January 1981 U.S. dollars per metric ton product on a weight-averaged basis)

Region and country	Mine	Mill	Other[1]	Total operating cost (f.o.b. mill)	Transportation cost to plant or port[2]	Total operating cost including transportation	Average cost[3] total at plant or port
North America: United States:							
Southeast:[4]							
Producers..........	$8.60	$12.30	$1.80	$22.70	$3.50	$26.20	$28.90
Nonproducers.......	9.10	13.80	7.30	30.20	4.20	34.40	50.30
West:[5]							
Producers..........	11.20	16.70	1.20	29.10	11.70	40.80	43.00
Nonproducers.......	17.90	13.40	6.60	37.90	10.20	48.10	63.90
North Africa: Morocco and Western Sahara:							
Producers..........	10.60	5.70	7.70	24.00	2.10	26.10	32.40
Nonproducers.......	9.10	7.50	14.30	30.90	2.40	33.30	46.60
Middle East:							
Israel, Egypt, and Jordan:							
Producers..........	10.20	13.00	3.10	26.30	6.00	32.30	44.80
Nonproducers.......	W	W	W	W	W	W	W
Syria, Iraq, and Turkey:							
Producers..........	10.00	9.60	9.00	28.60	14.20	43.30	55.20
Nonproducers.......	W	W	W	W	W	W	W
Oceania:							
Christmas Island and Nauru: Producers...	6.90	8.60	8.80	24.30	0.00	24.30	27.30
Australia:							
Producers..........	W	W	W	W	W	W	W
Nonproducers.......	7.60	12.40	6.40	26.40	12.30	38.70	53.50
South America: Brazil, Peru, and Venezuela:							
Producers..........	10.50	26.90	8.80	46.20	3.40	49.60	66.80
Nonproducers.......	13.50	22.90	19.30	55.70	2.40	58.10	84.20
West Africa: Senegal and Togo: Producers..	10.10	12.30	1.60	24.00	2.00	26.00	30.80

W Withheld to avoid disclosing individual deposit data.

[1]Includes all property, State, Federal, and severance taxes plus any royalty.

[2]Transportation costs to selected ports or acid plants that have been assumed as the product destination points for this study. (See table 12.)

[3]Includes a 15% DCFROR on all capital investments over the life of the property.

[4]Includes Florida, North Carolina, and Tennessee.

[5]Includes Idaho, Utah, and Wyoming

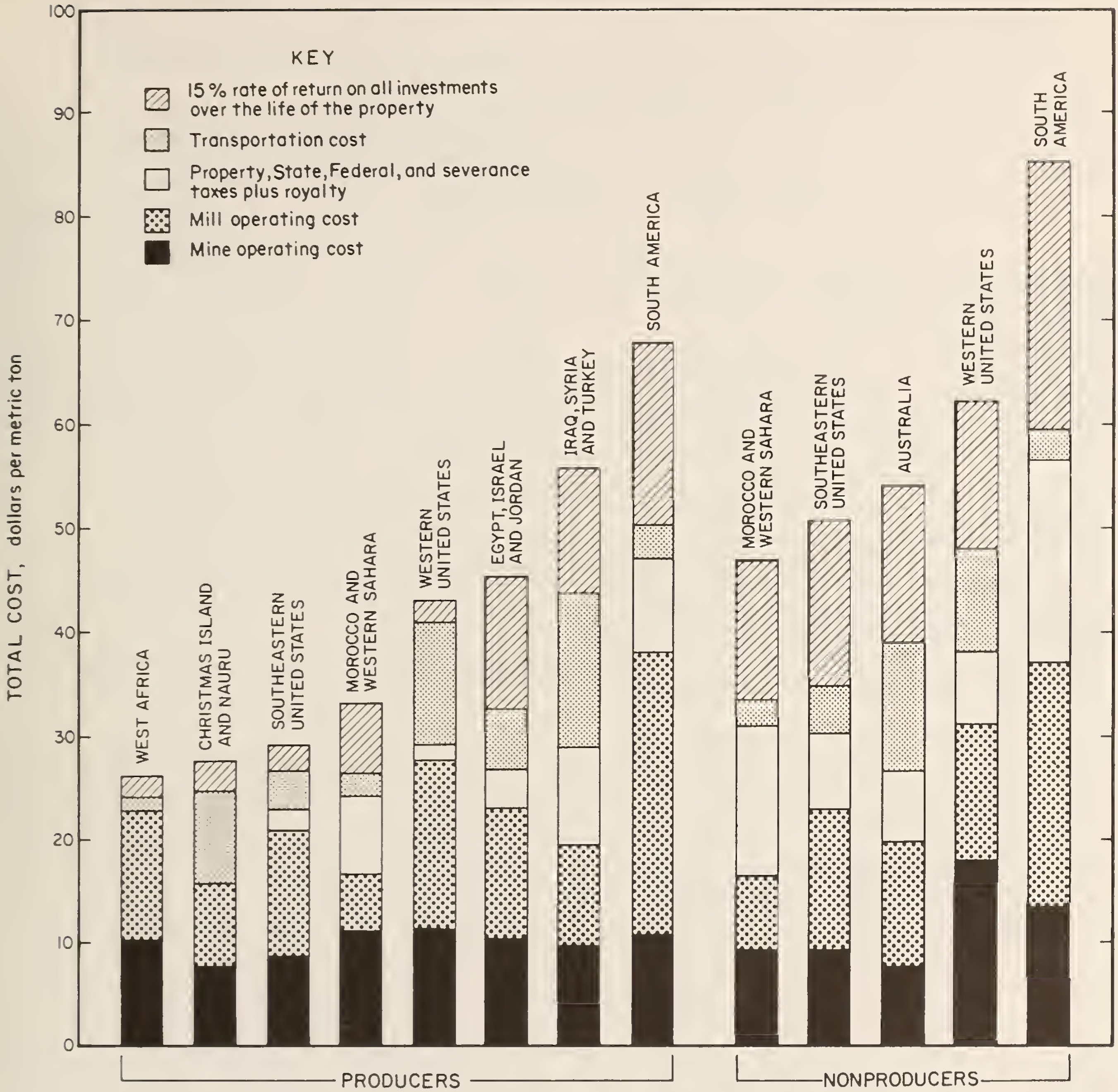


FIGURE 21. - Production costs for selected world phosphate surface mines and deposits.

TABLE 6. - Production costs for selected world phosphate underground mines and deposits

(All costs are expressed as January 1981 U.S. dollars per metric ton product on a weight-averaged basis)

Region and country	Mine	Mill	Other[1]	Total operating cost (f.o.b. mill)	Transportation cost to plant or port[2]	Total operating cost including transportation	Average total cost[3] at plant or port
North America: United States[4] and Mexico:							
Producers..........	W	W	W	W	W	W	W
Nonproducers........	$44.00	$30.30	$13.80	$88.10	$11.40	$99.50	$130.80
North Africa:							
Morocco: Producers.	11.90	9.20	6.30	27.40	1.50	28.90	34.10
Tunisia: Producers.	15.50	12.10	5.60	33.20	10.10	43.30	58.80
Middle East: Egypt:							
Producers..........	15.60	20.00	7.00	42.60	0.90	43.50	68.30
Nonproducers........	W	W	W	W	W	W	W

W Withheld to avoid disclosing individual deposit data.
[1]Includes all property, State, Federal, and severance taxes plus any royalty.
[2]Transportation costs to selected ports or acid plants that have been assumed as product destination points for this study. (See table 12.)
[3]Includes a 15% DCFROR on all capital investments over the life of the property.
[4]Includes Montana, Utah, and Wyoming.

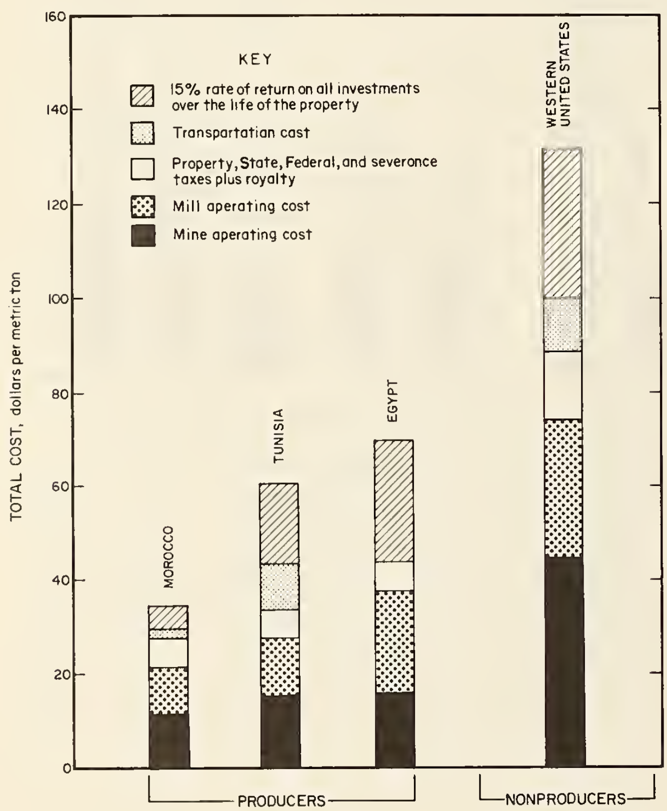


FIGURE 22. - Production costs for selected world phosphate underground mines and deposits.

CAPITAL COSTS

Table 7 shows the average capital costs estimated for this study to develop nonproducing surface deposits. These costs represent the costs to acquire, explore, develop, and equip a new mine site, along with construction of any mine and mill plants and buildings necessary. The table shows that in most cases the capital cost for the mill (plant and equipment) is the largest cost in developing a phosphate deposit (40% to 60% of total capital investment). Not shown on the table are infrastructure costs, which in countries like Australia or Brazil can be very large and can make the difference between developing and not developing.

COMPARISON OF FLORIDA AND MOROCCAN COSTS

A comparison was made between costs at nonproducing surface deposits in Florida and Morocco (table 8). The operating costs shown are f.o.b. mill; transportation charges have not been included. The capital cost shown is the cost required to bring the operation into production;

TABLE 7. - Capital costs to develop nonproducing surface phosphate mines in selected countries, January 1981 dollars

	Thousand metric tons per year		Capital cost, million dollars				Cost, per annual ton	
	Ore	Product	Exploration acquisition, and development	Mine	Mill	Total[1]	Ore	Product
United States (Southeast):								
Small......	2,500	450	$9.6	$8.9	$21.3	$39.8	$15.90	$88.40
Medium.....	5,600	1,000	32.2	16.1	38.3	86.6	15.50	86.60
Large......	15,600	2,400	74.6	34.5	71.4	180.5	11.60	75.20
Brazil.......	3,200	530	11.8	9.1	54.7	75.6	23.60	142.60
Morocco......	6,200	3,300	45.7	75.1	74.4	195.2	31.50	59.20
Australia....	8,700	3,700	5.1	26.4	42.0	73.5	8.50	19.90

[1]Excludes any infrastructure.

TABLE 8. - Comparison of nonproducing Florida and Morocco surface phosphate deposit costs

(All costs are in U.S. January 1981 dollars, f.o.b. mill)

	Florida No. 1[1]	Florida No. 2[2]	Morocco[3]
Mine or mill operating cost, dollars per metric ton product:			
Labor..................................	$3.10	$4.50	$3.50
Electricity............................	3.90	5.80	1.60
Diesel.................................	.10	.10	1.90
Supplies...............................	4.70	7.20	4.60
Drying fuel............................	1.90	2.90	3.40
General and administrative (G&A)........	4.10	6.10	4.90
Total..............................	17.80	26.60	19.90
Capital cost, million dollars:			
Acquisition............................	44	44	[4]19
Exploration............................	4	6	1
Development............................	11	17	47
Mill plant.............................	83	121	49
Mine equipment.........................	33	50	53
Infrastructure.........................	NAp	NAp	28
Working capital........................	17	17	19
Total..............................	192	255	216

NAp Not applicable.
[1]Deposit that will probably be developed during the next 10 yr.
[2]Deposit that will probably be developed in 20 to 40 yr.
[3]Deposit that will probably be developed during the next 5 to 10 yr.
[4]This cost may not be applicable from the standpoint of the Government of Morocco.

reinvestments and costs of planned expansions are not included. The costs represent a typical mine that would produce between 2.5 and 3 million tons of rock product per year. The Florida No. 1 deposit is an example of a mine that would be developed in the next 10 years, while the No. 2 deposit would not be mined for 20 to 40 years. The Moroccan deposit is an example of one to be mined in the next 5 to 10 years. The Florida deposits have lower grade reserves typical of the areas immediately south of the active mining district in central Florida (the southern extension), with magnesium oxide content of these deposits acceptable for conventional processing. The Florida No. 2 deposit has a feed grade and mill recovery value significantly lower than the Florida No. 1 deposit, although both produce a rock product containing approximately 30% P_2O_5.

As shown in the table, the Florida No. 1 deposit has only slightly lower total operating costs than the Moroccan deposit, while costs at Florida No. 2 are one-third greater, which in part reflects the lower grade and recovery at No. 2. The table shows that fuel costs are greater in Morocco, but electricity costs are greater in the Florida deposits. In reality, the fuel costs per *unit* do not differ greatly between the Moroccan and Florida operations, although the cost per ton is greater at the Moroccan operation because most of the equipment is diesel fuel operated (the draglines, shovels, etc.). Most Florida mining equipment is electrically powered (draglines, flotation units, etc.), and therefore electrical costs per ton of product are greater. Since much of the Moroccan rock is dried for export, drying costs are an additional factor.

It is important to note that the Moroccan mine has a much larger resource at a higher ore grade than either of the Florida deposits; at the production rates used in this comparison (2.5 to 3 million tons of rock per year) the Moroccan mine would produce for over 300 years while Florida No. 1 and No. 2 would last for only 20 and 40 years, respectively.

PHOSPHATE ROCK AVAILABILITY

ECONOMIC EVALUATION METHODOLOGY

After capital and operating costs were determined, the data were entered into the MAS Supply Analysis Model (SAM). The Bureau of Mines developed the SAM to perform discounted cash flow rate of return (DCFROR) analyses to determine the price of the primary commodity required for each operation to obtain a specified rate of return on its investments (33). This determined value for the phosphate rock price is equivalent to the average total cost of production for the operation over its producing life under the set of assumptions and conditions (e.g., mine plan, full capacity production, and a market for all output) that is necessary in order to make an evaluation. The DCFROR is most commonly defined as the rate of return that makes the present worth of cash flow from an investment equal to the present worth of all after-tax investments (34). For this study, a 15% DCFROR was considered the necessary rate of return to cover the opportunity cost of capital plus risk.

Based on the MAS methodology, all capital investments incurred 15 years before the initial year of the analysis (January 1981) are treated as sunk costs. Capital investments incurred less than 15 years before January 1981 have the undepreciated balances carried forward to January 1981, with all subsequent investments reported in constant January 1981 dollar terms. This computation means that for producing operations, the undepreciated capital investment remaining in 1981 was calculated. All reinvestment, operating, and transportation costs are expressed in January 1981 dollars. No escalation of either costs or prices was included because, assumedly, any increase in costs would be offset by an increase in price.

A separate tax-records file, maintained for each State and/or nation, contains the relevant fiscal parameters under which the mining firm would operate. This file includes corporate income taxes, property taxes, and any royalties, severance taxes, or other taxes that pertain to phosphate rock production. These tax parameters are applied to each mineral deposit under evaluation, with the implicit assumption that each deposit represents a separate corporate entity. The system also contains an additional file of economic indices to allow for continuous updating of all cost estimates to a base date (January 1981 for this study).

Beginning with 1981, the first year of the analysis, detailed cash flow analyses were generated for each preproduction and production year of an operation. Upon completion of the individual property analyses, all properties included in the study were simultaneously analyzed and aggregated onto resource availability curves. The total resource availability curve is a tonnage-cost relationship that shows the total quantity of recoverable product potentially available at each operation's average total cost of production over the life of the mine, determined at the stipulated (15%) DCFROR. Thus, the curve is an aggregation of the total potential phosphate rock that could be produced over the entire producing life of each operation, ordered from operations with the lowest average total cost of production to those with the highest. The curve provides a concise, easy-to-read, graphic analysis of the comparative costs associated with any given level of potential output and provides an estimate of what the average long-run phosphate rock price (in January 1981 dollars) would likely have to be in order for a given tonnage to be potentially available to the marketplace. Two types of curves have been generated for this study: (1) total availability curves and (2) annual curves at selected production costs. Annual curves are simply a disaggregation of the total curve to show annual phosphate rock availability at varying costs of production.

Certain assumptions are inherent in the curves. First, all deposits produce at full operating capacity throughout the productive life of the deposit. Second, each operation is able to sell all of its output at a price equal to or greater than its average total production cost. Third, development of each nonproducing deposit began in the same base year (N) (unless the property was developing at the time of the evaluation). Since it is difficult, if not impossible, to predict when the explored deposits are going to be developed, this assumption was necessary. Also, the preproduction period allows for only the minimum engineering and construction period necessary to initiate production under the proposed development plan. Consequently, the additional time lags and potential costs involved in filing environmental impact statements, receiving required permits, financing, etc., have not been included in the individual deposit analyses.

The potential tonnage and the estimated average total cost over the life of the mine for each of the 201 mines and deposits evaluated have been aggregated onto phosphate rock availability curves, which illustrate the comparative costs associated with any given level of potential total output. Costs reflect not only capital and operating costs, but also all pertinent taxation and the cost of transporting the rock product to the nearest port or acid plant. A comparison of costs on an f.o.b. mill basis and a discussion of ocean freight charges appear later in this section. Potential availability of phosphate rock from China and the U.S.S.R. is described in the text but is not included on curves owing to the difficulty in gathering accurate cost data and developing U.S. dollar equivalents.

TOTAL AVAILABILITY

At the demonstrated resource level, approximately 34.2 billion tons of phosphate rock is potentially recoverable from the 201 mines and deposits in market economy countries, with Morocco and Western Sahara (21 billion tons) accounting for 61% of the total, followed by the United States (6.4 billion tons) at 19%. In addition, the 17 deposits evaluated in the U.S.S.R. and China contain approximately 1.5 billion tons of potentially recoverable phosphate rock.

Market Economy Countries

The tonnage of phosphate rock potentially available from the deposits analyzed in market economy countries is shown in figure 23. A total of 32.9 billion tons of phosphate rock is potentially recoverable at total production costs ranging from $17 to $100 per ton (in January 1981 dollars) from 175 mines and deposits. Approximately 1.6 billion tons is potentially recoverable at costs ranging up to $30 per ton (55% from the United States), 10.6 billion tons at costs ranging up to $40 (13% from the United States), and 15.7 billion tons at costs up to $50 (21% from the United States). An additional 1.3 billion tons could potentially be produced at a cost of over $100 per ton from 26 deposits which are not shown on the curves.

The curve for north Africa includes potential production from Algeria, Morocco, Tunisia, and Western Sahara. Approximately 21.3 billion tons of phosphate rock (94% from Morocco) is potentially recoverable from the 20 north African

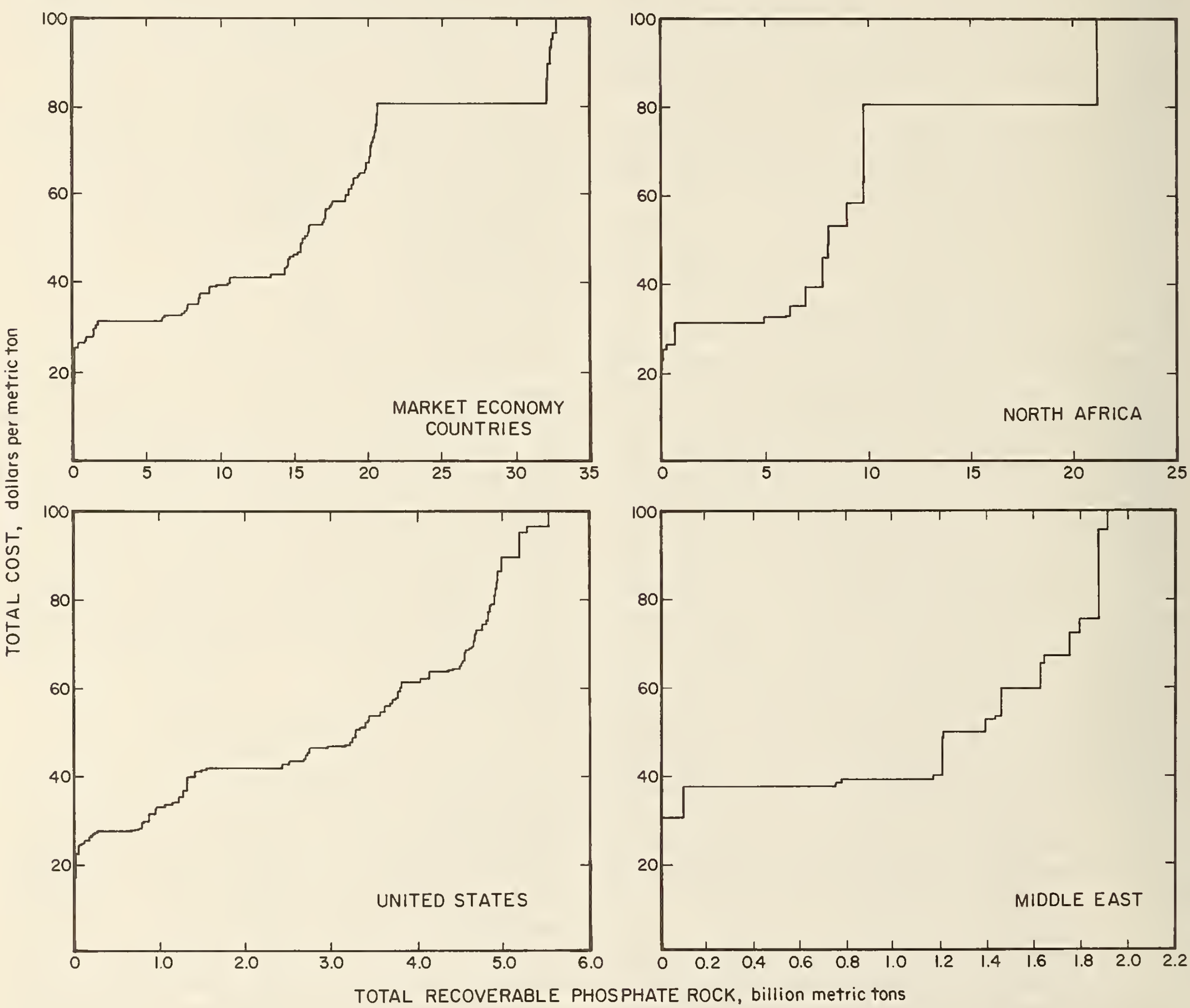


FIGURE 23. - Phosphate rock potentially recoverable from all mines and deposits in market economy countries. Note that curves are drawn at different scales.

mines and deposits evaluated, or 62% of the market economy country total. At costs ranging from $24 to $30 per ton, 612 million tons of phosphate rock is potentially recoverable, 7.8 billion tons is potentially recoverable at costs up to $40 per ton, and 8.1 billion tons is potentially recoverable at costs up to $50 per ton.

The curve for the United States shows 5.6 billion tons of phosphate rock potentially recoverable from 110 mines and deposits at costs ranging from $17.50 to $96.50 per ton. Approximately 875 million tons of phosphate rock is potentially recoverable at costs ranging up to $30 per ton, 1.4 billion tons at costs up to $40 per ton, and 3.3 billion tons at costs up to $50 per ton. Another 822 million tons potentially recoverable from 20 deposits (mostly in Wyoming and Utah) at costs greater than $100 per ton is not shown on the curve.

The curve for the Middle East illustrates potential production of 1.9 billion tons at costs ranging from $30 to $96 per ton from 16 mines and deposits in Egypt, Iraq, Israel, Jordan, Saudi Arabia, Syria, and Turkey. An additional 234 million tons of estimated potential production from one deposit in Egypt is not shown on the curve because its estimated cost of production is over $100 per ton. Potential recoverable phosphate from the Middle East amounts to 6% of the market economy country total.

The three regions highlighted in figure 23 account for 87% of the recoverable demonstrated phosphate rock resources of market economy countries. Other regions included in the total availability curve for market economy countries but not shown on separate curves are South America, Oceania (which includes Australia and Nauru), Mexico, Senegal, the Republic of South Africa, and Zimbabwe. South America has an estimated production potential of 654 million tons of phosphate rock from 14 mines and deposits in Brazil (11 mines and deposits), Peru, Colombia, and Venezuela (1 deposit each). Oceania has an estimated production potential of 567 million tons from six mines and deposits in Australia and one mine in Nauru. The combined potential tonnage from Senegal (two mines), the Republic of South Africa, Togo, and Zimbabwe (one mine each) amounts to 2.8 billion tons.

Figure 24 presents availability curves for all market economy countries, north Africa, the United States, and the Middle East, comparing potentially recoverable phosphate rock from producing mines with that from developing mines and explored deposits. Of the 34.2 billion tons of phosphate rock estimated to be potentially available from market economy countries, 39% is from producing mines and 61% is from undeveloped deposits. The curve for north Africa shows that producing mines account for 7.1 billion tons of potential recoverable phosphate rock (34% of the total potential for north Africa of 21.3 billion tons) and that developing mines and explored deposits account for 14.2 billion tons (67% of the north Africa total). For the United Staes, out of a potential total of 6.4 billion tons of phosphate rock, 1.3 billion tons is from producing mines (21%), and undeveloped deposits account for slightly over 5 billion tons (79%). Of the 2.1 billion tons of phosphate rock potentially available from the Middle East, 1.4 billion is from producing mines (66%) and 773 million (36%) is from undeveloped deposits.

Centrally Planned Economy Countries

The 7 mines in China (6 producing and 1 developing) investigated at the demonstrated level for this study contain 208 million tons of potentially recoverable phosphate rock, and the 11 mines in the U.S.S.R. (10 producing and 1 developing) contain 1.3 billion tons. Estimated costs of production range from $11.50 to $86.50 per ton of phosphate rock product. Generally, the Chinese mines have lower total production costs than those of the U.S.S.R., with the exception of the developing Kunming deposit, which ranks with the higher cost Soviet mines. Resources of phosphate rock in both China and the U.S.S.R. are relatively small compared with those of the United States

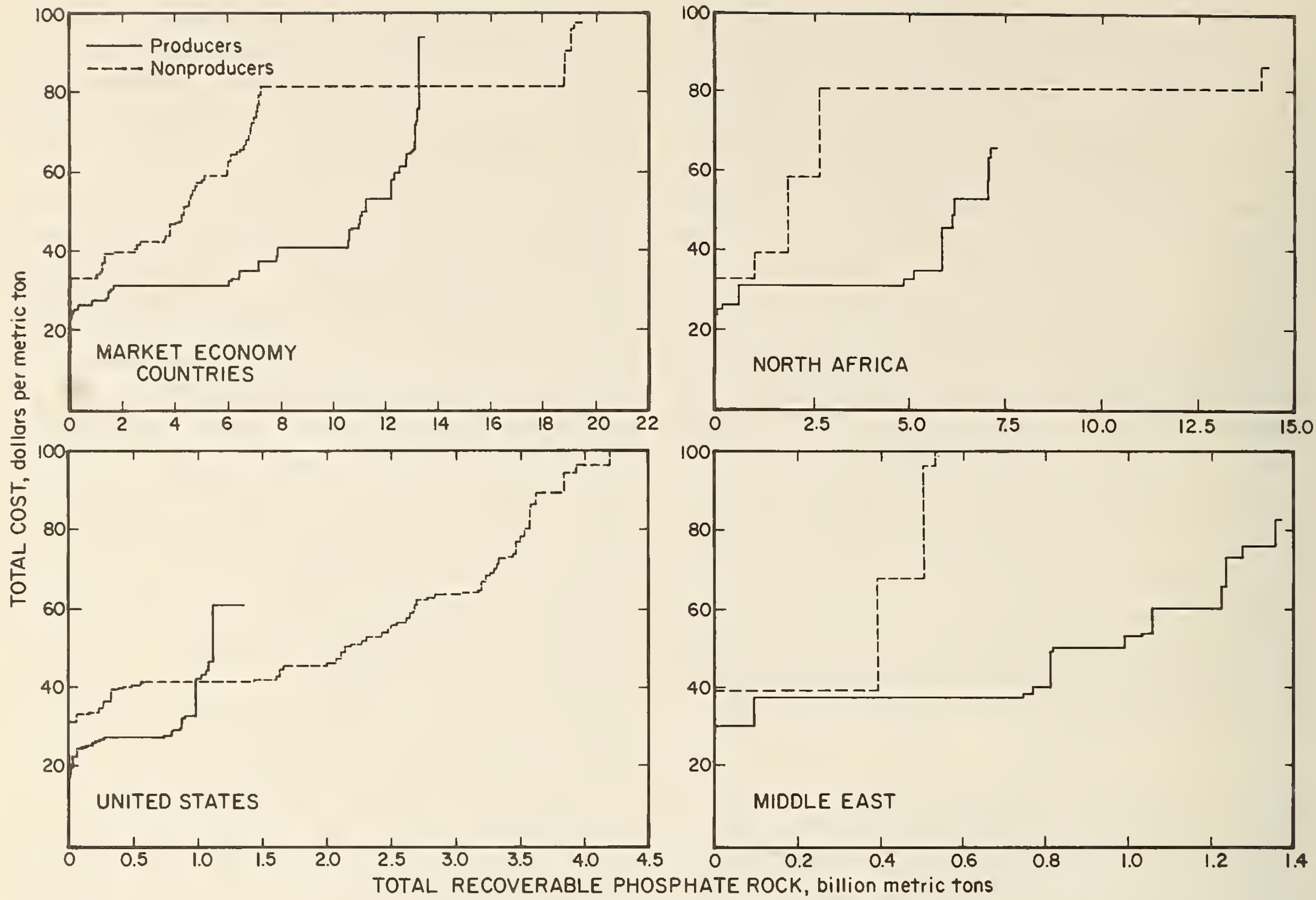


FIGURE 24. - Phosphate rock potentially recoverable from producing mines and nonproducing deposits in market economy countries. Note that curves are drawn at different scales.

and Morocco. The U.S.S.R. is the dominant factor in supplying the Eastern European market. It is doubtful that either China or the U.S.S.R. will become a major supplier in the world market for phosphate rock and related fertilizers; more likely, these countries represent potential export markets for Western phosphate producers.

ANNUAL AVAILABILITY

Another way of illustrating phosphate availability is to disaggregate the total resource availability curve and show potential availability on an annual basis. For analysis, separate annual availability curves have been constructed for producing and proposed operations in market economy countries. Separate annual availability curves have been constructed for all producing mines in market economy countries, north Africa, the United States, and the Middle East. For undeveloped deposits, only one curve for the market economy countries was constructed. Since no realistic development schedule can be proposed for all of the undeveloped deposits, the emphasis of this curve is to indicate capacity and cost levels of potential future deposits.

Potential annual production of phosphate from producing mines in market economy countries, north Africa, the United States, and the Middle East from 1981 to 1995 is shown in figure 25. The curves reflect the production capacity of existing mines, including planned expansions when known. It was assumed that all operations produce at full (100-pct) capacity over the life of the mine.

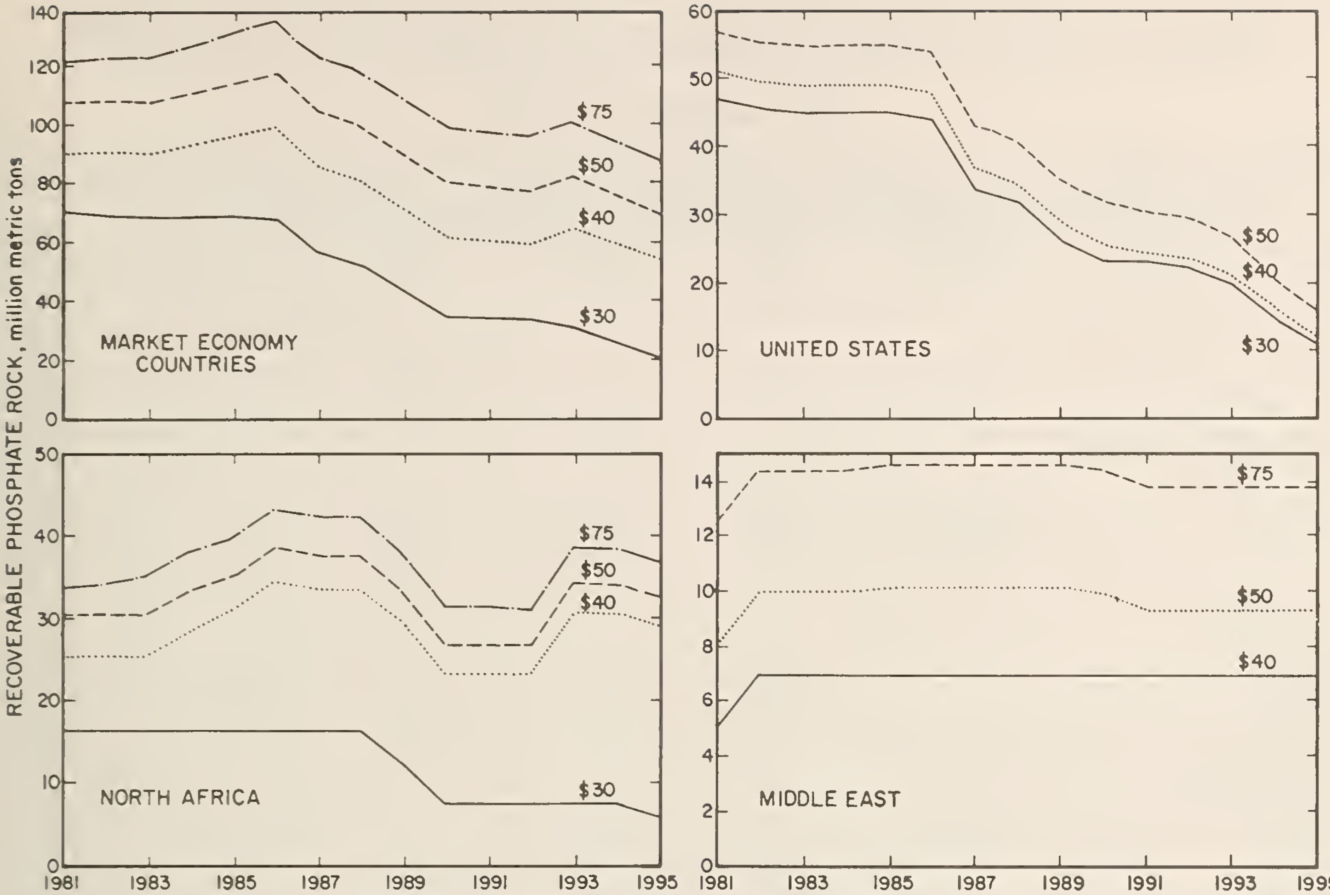


FIGURE 25. - Potential annual production from producing mines in market economy countries at various cost levels. Note that curves are drawn at different scales.

Since actual production may be at less than capacity levels, the curves shown in this section would not actually decline as rapidly as shown. The curves shown in figure 25 illustrate the fact that potential production from producing mines in the United States will likely decline dramatically after 1986, while production from north Africa, in particular, will continue to increase through 1987. The U.S. phosphate industry has been producing at much less than full capacity since mid-1981, however, so the decline in potential U.S. production shown on the curve will actually be delayed for several more years and the eventual decline will be more gradual than shown. Although potential annual capacity in north Africa will decrease between 1987 and 1993, additional capacity expansions are schedulaed after 1993.

The estimated annual production capacities for each producing country at different cost levels in 1983 and 1995 are shown in tables 9 and 10. The production capacities listed for each cost level were used to construct the annual curves. As shown in table 9, the estimated capacity for mines in market economy countries in 1983 is 122.7 million tons of phosphate rock at production costs ranging up to $75 per ton. This compares with actual production of 101.1 million tons of phosphate rock in 1981. The estimated capacity for the United States in 1983 of 55.3 million tons is slightly higher than the 1981 production of 54 million tons.

Although not shown on the curves, an additional 1.6 million tons of phosphate rock could be produced at production costs over $75 per ton from mines in Brazil, Egypt, and Finland. These high-cost producers either are subsidized or compete against high-cost phosphate rock imports (such as in Brazil).

TABLE 9. - Estimated potential annual production capacities in market economy countries by 1983, for mines that produced in 1981

(Thousand metric tons)

Region and country	Cost per ton					Total
	$17-$30	$30.01-$40	$40.01-$50	$50.01-$60	$60.01-$75	
North America:						
United States....	44,842	3,986	5,956	159	329	55,272
Mexico...........	--	--	--	--	801	801
South America:						
Brazil...........	--	--	--	1,204	2,425	3,629
Colombia.........	--	--	141	--	--	141
Venezuela........	--	--	--	--	468	468
North Africa:						
Algeria..........	--	--	2,005	--	--	2,005
Morocco..........	16,434	8,919	--	1,998	--	27,351
Tunisia..........	--	--	3,031	849	1,901	5,781
Other African countries:						
Senegal..........	--	1,830	--	--	--	1,830
South Africa.....	--	--	3,261	--	--	3,261
Togo.............	3,001	--	--	--	--	3,001
Zimbabwe.........	--	--	--	--	179	179
Middle East:						
Egypt............	--	100	129	--	230	459
Iraq.............	--	--	--	1,701	--	1,701
Israel...........	--	1,000	--	2,501	--	3,501
Jordan...........	--	5,819	770	--	--	6,589
Syria............	--	--	2,135	--	--	2,135
Oceania:						
Australia........	1,400	--	--	--	250	1,650
Nauru............	2,491	--	--	--	--	2,491
Other: India......	--	--	--	--	475	475
Total..........	68,168	21,654	17,428	8,412	7,058	122,720

NOTE.--Dashes indicate that the cost range contains no tonnage.

Table 10 shows potential production of 88.5 million tons of phosphate rock in 1995 at production costs ranging up to $75 per ton. The interesting comparison between tables 9 and 10 is the decline in potential production capacity for the United States compared to the increase for Morocco. The United States shows a decline from 55.2 million tons in 1983 to 16.4 million tons in 1995 as the demonstrated resources of producing mines become exhausted. Morocco, on the other hand, shows an increase from 27.3 million tons in 1983 to 31.3 million tons in 1995.

Potential production of phosphate rock in 1995 at costs of under $30 per ton would decline to 21.1 million tons compared with 68.2 million tons in 1983. The U.S. share of this production would decline to 51.5%, while Morocco's share would be 29.3%. Of the 33.4 million tons of phosphate that could be produced in 1995 at costs between $30 and $40 per ton, the United States would account for only 4.1% and Morocco would account for over 69%. At estimated production costs between $40 and $50, 15.9 million tons of phosphate rock could be produced in 1995, with the United States accounting for

TABLE 10. - Estimated potential annual production capacities in market economy countries by 1995, for mines that produced in 1981

(Thousand metric tons)

Region and country	Cost per ton					Total
	$18-$30	$30.01-$40	$40.01-$50	$50.01-$60	$60.01-$75	
North America:						
United States.....	10,850	1,360	3,746	159	329	16,444
Mexico............	--	--	--	--	801	801
South America:						
Brazil............	--	--	--	2,208	3,427	5,635
Colombia..........	--	--	564	--	--	564
Venezuela.........	--	--	--	--	468	468
North Africa:						
Algeria...........	--	--	2,005	--	--	2,005
Morocco...........	6,172	23,127	--	1,998	--	31,297
Tunisia...........	--	--	1,547	--	1,401	3,797
Other African countries:						
Senegal...........	--	1,979	--	--	--	1,979
South Africa......	--	--	5,608	--	--	5,608
Togo..............	4,065	--	--	--	--	4,065
Middle East:						
Egypt.............	--	100	129	--	270	499
Iraq..............	--	--	--	1,701	--	1,701
Israel............	--	1,000	--	2,501	--	3,501
Jordan............	--	5,819	770	--	--	6,589
Syria.............	--	--	1,492	--	--	1,492
Oceania: Australia.	--	--	--	--	1,000	1,000
Other: India.......	--	--	--	--	1,103	1,103
Total............	21,087	33,385	15,861	9,416	8,799	88,548

NOTE.--Dashes indicate that the cost range contains no tonnage.

23.6% and Morocco having zero potential production in this cost range. Brazil would dominate production in the $50 to $75 cost range with 30.9% of the potential 1995 production.

If the market permitted it, some of the estimated decline of production by producing mines in the United States could be counteracted by an expansion of production capacities of the remaining producers that have large resources, although such an expansion would effectively shorten their producing lives. Future U.S. needs will have to be met through the development of new mines, which in most cases will have higher total costs, or possibly through importation.

The potential annual availability curve for all of the undeveloped deposits in market economy countries is shown in figure 26. Since no definite startup is known or available for most of these deposits, it was assumed that preproduction began in a base year (*N*) of the analysis which cannot be connected with an actual year since production from many of these deposits is not expected in the near future. However, the annual curves for undeveloped deposits do show the required lead times before production can begin and therefore are important in that they show the potential production costs and potential annual capacities of the mines of the future. In these curves, all undeveloped deposits (with the exception of

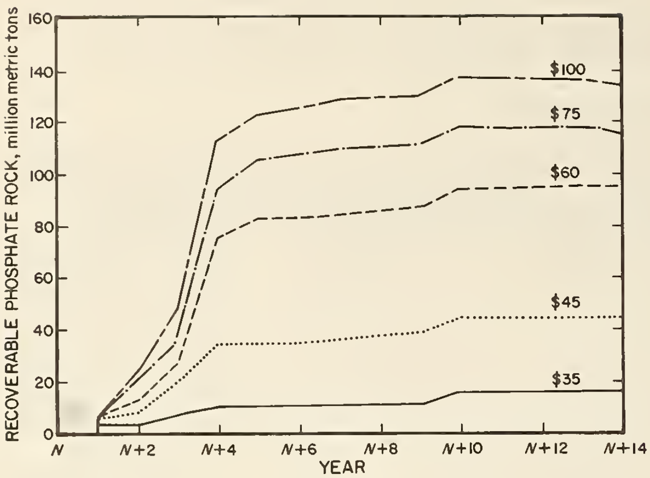


FIGURE 26. - Potential annual production from developing mines and explored deposits in market economy countries at various cost levels.

the mines that are currently under development) assumedly begin preproduction development at the same time; consequently the tonnage available in a given year is overstated since not all of the nonproducers will begin preproduction development simultaneously. Mines that are currently developing appear in the first couple of years, and then potential annul production increases dramatically as the other nonproducers begin to come onstream in the year *N*+4. The key factor that this curve highlights is the tonnage differential at the different cost levels. Under the assumption that all of the nonproducing deposits began preproduction development in year *N*, all would be producing at full capacity by the year *N*+10 (although some capacity expansions would continue to occur beyond that time). In this case, 136.9 million tons of phosphate rock could be produced in the year *N*+10 at production costs ranging up to $100 per ton. (An additional 21.2 million tons at estimated production costs greater than $100 is not shown on the curve.) Of this amount, 15.3 million tons could be produced at costs under $35 per ton: 67% from the United States, 31% from Morocco, and 2% from Australia. At production costs between $35 and $45 per ton, 28.8 million tons of phosphate rock could be produced: 76% from the United States, 14% from Jordan, and 10% from the Western Sahara. From $45.01 to $60 per ton, 49.3 million tons of phosphate rock could be produced: 71% from the United States, 22% from Australia, and 6% from Morocco. From $60.01 to $75 per ton, an additional 24 million tons of phosphate could be produced: 8% from the United States, 14% from Peru, and the remaining 18% from Saudi Arabia, Mexico, and Pakistan. Of the 19.5 million tons that could be produced from $75 to $100 per ton, 82% would be from the United States, mainly from deposits in the West. The data underlying figure 26 are shown in tabular form in table 11. The United States predominates in the potential production of phosphate rock at costs under $50. Potential U.S. production in the year *N*+10 at $50 or less is slightly over 49 million tons, which is 81% of the total for all of the market economy countries at that cost level.

Based on the data presented in tables 9 and 10, the United States will have to invest in the development of new mines within the next few years in order to maintain or increase current production. Assuming fixed capacities for existing mines, if U.S. production in 1995 remained the same as in 1981 (at 54 million tons of phosphate rock), almost 70% of the production in 1995 would come from mines that have yet to be developed.

Obviously, much of the potential tonnage shown in figure 26 for the year *N*+10 will not actually be produced for a very long time, especually from the high-cost deposits. If we can assume, however, that most of the deposits that could produce for under $50 per ton will actually be developed over the next 20 years or so, it appears that the undeveloped deposits in the United States have a future cost advantage over the undeveloped deposits in other countries, at least when measuring production costs f.o.b. port or acid plant. However, based on the foregoing analyses, the U.S. phosphate industry in Florida will have to invest in the next few years to develop new deposits if it intends to maintain or expand upon current production levels, while Morocco

TABLE 11. - Estimated potential annual production capacities for undeveloped deposits at an average total production cost of less than $100 per ton of phosphate rock in the year N+10, by country

(Thousand metric tons)

Region and country	Cost per ton					Total
	$27-$35	$35.01-$45	$45.01-$60	$60.01-$75	$75.01-$100	
North America:						
United States....	10,311	21,831	34,998	16,342	16,048	99,530
Canada...........	--	--	--	--	702	702
Mexico...........	--	--	--	1,204	--	1,204
South America:						
Brazil...........	--	--	--	--	498	498
Peru.............	--	--	--	3,435	--	3,435
North Africa:						
Morocco..........	4,677	--	3,070	--	2,094	9,841
Western Sahara...	--	2,929	--	--	--	2,929
Other African countries: Angola.	--	--	228	--	--	228
Middle East:						
Jordan...........	--	4,000	--	--	--	4,000
Saudi Arabia.....	--	--	--	2,500	--	2,500
Turkey...........	--	--	--	--	130	130
Other Middle East: Pakistan...	--	--	--	556	--	556
Oceania: Australia	300	--	11,000	--	--	11,300
Total...........	15,288	28,760	49,296	24,037	19,472	136,853

NOTE.--Dashes indicate that the cost range contains no tonnage.

may need to invest primarily to expand production of existing mines. Almost two-thirds of the phosphate from new mines in the United States that could be produced for under $50 per ton would cost in the $40 to $50 range, whereas most phosphate rock in Morocco from existing mines can be produced for under $40 per ton. Therefore, although current production costs are similar, the United States might have to spend large amounts of capital to maintain production, while Morocco will not. As a result, the cost advantage in the world phosphate export industry will likely shift from Florida to Morocco.

There are numerous factors, however, that could greatly enhance the outlook for phosphate availability from the United States, particularly over the long run. In addition to the demonstrated resources evaluated in this study for the United States, an estimated 7 billion tons of potentially recoverable phosphate rock exists at the inferred level (over 80% is in the Southeast), and over 24 billion tons of potentially recoverable phosphate rock exists at the hypothetical resource level (over 60% is in the Southeast).

New deposits will likely be discovered (particularly offshore deposits along the eastern seaboard), low-grade material could become economically minable, or technological advances could enable processing high-magnesium oxide material or the mining of deep deposits by the borehole mining technique. Each of these factors could greatly increase the amount of phosphate available in the future.

Of immediate interest to the U.S. phosphate industry is more than 2 billion tons of recoverable phosphate rock in

Florida at the identified resource level that contains high-magnesium-oxide material and is presently considered unacceptable by the industry owing to the higher beneficiation costs of producing an acceptable acid plant feed. Given the progress several phosphate companies and the Bureau of Mines have made in developing beneficiation technologies to lower the grade of magnesium oxide in the phosphate rock product, this additional 2 billion tons of rock could likely become available in the near future, but at a higher cost.

EFFECT OF TRANSPORTATION

The foregoing analyses determined the average total production cost for phosphate rock, including a transportation charge for each deposit to the nearest port or acid plant (or to market in some cases). The assumed destinations of the rock product (port, acid plant, or market), by country, are shown in table 12.

Figure 27 provides a cost comparison between phosphate rock production from each mine or deposit both f.o.b. port or acid plant and f.o.b. mill. Table 13 presents a more definitive breakdown, showing average total production costs (including a 15% DCFROR), both f.o.b. mill and f.o.b. port or acid plant, on a weight-averaged basis. Although the cost differential between mines and deposits determined on an f.o.b. mill or an f.o.b. port or acid plant basis is significant, this differential is fairly consistent in all of the producing countries. A more important measure of the cost of phosphate is the cost of shipping phosphate from individual producing to consuming countries. Although shipping costs from producing to consuming countries were not included in the analysis that went into the construction of the availability curves for phosphate, they are presented for comparison purposes in table 14.

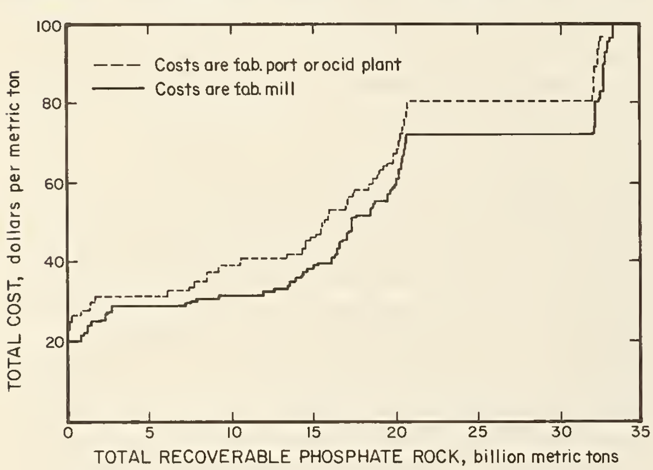


FIGURE 27. - Phosphate rock potentially recoverable from all mines and deposits in market economy countries.

The reader can ascertain a more accurate cost of phosphate rock to a consuming nation by taking the production cost data presented in table 13 and adding from table 14 the relevant shipping cost to the consuming country. In this way, a general comparison can be made as to the cost of phosphate rock from competing suppliers to a particular consumer. Of paramount interest for the U.S. phosphate industry are the relative costs between the United States and north African (primarily Moroccan) phosphate rock producers when freight charges to various major phosphate markets are included. For phosphate rock delivered to the port of Amsterdam, Moroccan phosphate rock has a $12 per ton cost advantage (exclusive of any tariffs) over U.S. phosphate rock. This differential increases to $19 between deposits in Morocco that are not yet producing and undeveloped deposits in the Southeastern United States. Considering that Morocco is gearing up to produce much more phosphoric acid for export, it appears that Morocco should further dominate the European market in the future. The same situation exists for exports to Eastern European countries.

The United States should maintain its comparative advantage in supplying its domestic market and the Canadian market and appears to have a relative cost advantage in the Far East. Both the United States and Morocco will likely lose the Brazilian market since Brazil is becoming self-sufficient in phosphate.

TABLE 12. - Assumed destinations for phosphate rock, by country

Country	Market[1]	Location of port or acid plant
North America:		
United States:		
Florida	E	Tampa or Jacksonville.
North Carolina	E	Morehead City.
Tennessee	IC	Mount Pleasant.
Idaho	IC	Pocatello or Soda Springs, ID; Silverbow, MT.
Montana	IC	British Columbia.
Utah	IC	Pocatello or Soda Springs, ID.
Wyoming	IC	Do.
Canada	IC	Port Maitland.
Mexico	IC	Port Belcher or Lazaro Cardenas.
South America:		
Brazil	IC	Uberaba, Santos, Imbitumba, Fortaleza, Rio de Janeiro, or Recife.
Colombia	IC	Pesca.
Peru	E	Port Bayovar.
Venezuela	IC	Moron.
North Africa:		
Algeria	E	Annaba.
Morocco	E	Casablanca, Safi, or Jorf Lasfar.
Tunisia	E	Sfax or Gabes.
Western Sahara	E	El Aaiun.
Other African countries:		
Angola	E	Lacunga River mouth.
Senegal	E	Port Dakar.
South Africa	E	Maputo.
Togo	E	Port Kpome.
Zimbabwe	IC	Salisbury.
Middle East:		
Egypt	E	Safaga.
Iraq	E	Khor-Al-Zuber Port.
Israel	E	Port of Ashdad.
Jordan	E	Aqaba.
Syria	E	Port Tarfous.
Turkey	IC	Elazig.
Oceania:		
Australia	E	Port at Gulf of Carpentaria or Townsville.
Christmas Island	E	Christmas Island.
Nauru	E	Nauru.
Miscellaneous countries:		
China	IC	Local.
Finland	E	Leningrad, or port in Gulf of Finland.
India	IC	Udaipur.
U.S.S.R.	IC	Local.

[1]E Export. IC Internal consumption.

TABLE 13. - Comparison of average total costs per metric ton of phosphate rock, f.o.b. mill and f.o.b. port or acid plant, by major producing region

Region and country	Potential phosphate rock production, 10^6 metric tons	Average total cost of production	
		f.o.b. mill	f.o.b. port or acid plant
United States:			
Southeast:			
Producers	981	$25.40	$28.90
Nonproducers	2,925	44.30	48.30
West:			
Producers	361	31.30	43.00
Nonproducers[1]	2,112	92.70	104.30
South America:			
Producers	412	61.00	64.30
Nonproducers	242	98.40	105.30
North Africa:			
Producers	7,125	32.00	34.60
Nonproducers	14,170	40.90	46.60
Other African countries:			
Producers	2,823	30.90	37.70
Nonproducers	10,000	50.00	59.50
Middle East:			
Producers	1,360	40.00	50.60
Nonproducers	773	60.50	69.40
Oceania:			
Producers	207	29.90	53.90
Nonproducers	344	27.40	53.80

[1]Costs are weighted high owing to the effect of high costs at underground mines in the West.

CONCLUSIONS

The agricultural industry worldwide is dependent upon the supply of fertilizers derived from phosphate rock. In an attempt to assess worldwide phosphate rock resources, the Bureau of Mines evaluated 201 mines and deposits in market economy countries and investigated the resource potential of 17 mines and deposits in China and the U.S.S.R. The selected mines and deposits include all known resources of phosphate rock at the demonstrated resource level that met the criteria of the study and that can be mined and milled with current technology.

Approximately 34.2 billion tons of phosphate rock is potentially recoverable from the demonstrated resources of 201 mines and deposits evaluated in market economy countries. An additional 1.5 billion tons of phosphate rock is potentially recoverable from 17 mines and deposits in China and the U.S.S.R. Morocco and Western Sahara have the largest resource, with 21 billion tons of recoverable phosphate rock, followed by the United States with 6.4 billion tons. Of the approximately 1.6 billion tons of phosphate rock that is potentially recoverable at total production costs (including a 15% DCFROR on all investments) of under $30 per ton, 55% is in the United States and 39% in Morocco. All of this potential low-cost resource is from mines that are currently producing. Approximately 10.6 billion tons of phosphate rock is potentially recoverable at production costs under $40 per ton, including 6.9 billion tons from Morocco (66%) and 1.4 billion tons from the United States (13%). Of this 10.6 billion tons, 7.2 billion tons (68%) is from currently producing mines, including 5.9 billion tons from producing mines in Morocco and

TABLE 14. - World phosphate rock shipping charges[1]

(U.S. dollars per metric ton shipped)

Producing country	Destination									
	Africa[2]	Australia (Sydney)	Brazil (Rio de Janeiro)	Eastern Europe (Costanza, Romania)	India (Paradip)	Japan (Osaka)	Mexico (Veracruz)	Turkey (Istan-bul)	United States (New York)	Western Europe (Amsterdam, Netherlands)
Algeria..	NAp	NAp	$24.60	$10.70	[3]$63.70	NAp	NAp	NAp	NAp	$8.40
Christmas Island..	NAp	$23.40	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp
Egypt....	NAp	NAp	NAp	16.90	[3]80.80	NAp	NAp	NAp	NAp	NAp
Israel...	NAp	NAp	53.70	22.20	43.80	$33.90	NAp	$17.60	NAp	20.00
Jordan...	$30.90	NAp	NAp	20.00	29.10	41.60	NAp	23.80	NAp	18.10
Morocco..	NAp	59.40	24.80	8.80	42.20	54.30	$52.30	25.30	$47.50	8.60
Nauru....	NAp	14.30	NAp	NAp	[3]30.00	25.10	NAp	NAp	NAp	NAp
Senegal..	NAp	NAp	NAp	13.30	43.40	60.30	NAp	NAp	NAp	11.20
Syria....	NAp	NAp	NAp	17.40	42.50	NAp	NAp	NAp	NAp	NAp
Togo.....	38.60	NAp	NAp	25.00	42.80	59.90	NAp	NAp	NAp	22.40
Tunisia..	NAp	NAp	30.40	12.50	NAp	NAp	NAp	15.00	NAp	10.20
United States (Tampa).	NAp	40.20	23.50	29.70	51.90	40.80	11.20	NAp	NAp	26.30
U.S.S.R..	NAp	NAp	NAp	26.20	NAp	NAp	NAp	NAp	NAp	23.60

NAp Not applicable.
[1]Cost includes loading and unloading charges and is in 1981 dollars.
[2]To Dar Es Salaam, Tanzania, from Jordan, and Port Harcourt, Nigeria, from Togo.
[3]To Korea.

Source: Data complied by Zellars-Williams, Inc., Lakeland, FL, under Bureau of Mines contract J0100122.

980 million tons from producing mines in the United States. There are 15.7 billion tons of phosphate rock estimated to be recoverable at total production costs of less than $50 per ton from market economy countries; Morocco accounts for 6.9 billion tons (44%), and the United States accounts for 3.3 billion tons (21%). Phosphate rock production potentially available at costs under $50 per ton from producing mines amounts to 11.2 billion tons, of which 5.9 billion tons is from Morocco (52%) and 1.1 billion tons (10%) is from the United States.

Potential annual capacity from producing mines in the United States could decline to 16.4 million tons by 1995 as the demonstrated resources of producing mines become exhausted. Since actual production may be at less than capacity levels, this decline will not be as rapid as indicated. However, the annual capacity for producing mines in Morocco in 1995 is estimated to increase to 31.3 million tons (compared with actual production in 1981 of 19.7 million tons). Assuming fixed capacities for existing mines, if U.S. production remained the same as in 1981 (at 54 million tons of phosphate rock), nearly 70% of the 1995 production would come from mines that have yet to be developed. Undeveloped deposits in the United States, if developed concurrently, would have a potential annual capacity of 49 million tons of phosphate rock in the year *N*+10 of the analysis, at production costs under $50 per ton. Slightly over one-third of this capacity could be produced for under $40 per ton, and slightly less than two-thirds would cost in the $40 to $50 range. In compsrison, most of the competing phosphate rock from existing mines in Morocco can be produced for under $40 per ton. This fact, combined with Morocco's cost advantage in shipping phosphate rock to many of the consuming markets, indicates that the cost advantage in the world phosphate export industry may likely shift from Florida to Morocco. Morocco is also constructing acid plants to process phosphate rock, which means that as domestic phosphate rock costs increase, the United States will also face serious competition in the export markets for phosphoric acid and related fertilizer products. However, it should be stressed that the above situation applies only to competition for certain major export markets. The United States remains the largest consumer of phosphate fertilizers and should remain as the main supplier of phosphate rock products to Canada and the Far East. Even if the U.S. phosphate industry does succomb to competition from Morocco in certain major markets, its economic viability is not in question. Also, a slower rate of growth would extend the life of domestic phosphate resources.

Although the demonstrated phosphate rock resources of producing mines in the United States are declining, developing mines and explored deposits in the United States contain a demonstrated resource of 2.2 billion tons of recoverable phosphate rock that could be developed and produced for under $50 per ton (including a 15% DCFROR). In addition, huge untapped resources are present at the inferred and hypothetical resource levels. Any technological breakthroughs (and some have occurred) that enabled lower cost beneficiation of high-magnesium-oxide phosphate or lowered the estimated production costs of low-grade or deeper lying phosphate would significantly enhance the export position of the United States.

The U.S. phosphate industry has been the world leader in the output and export of phosphate rock and related products but is incurring higher production costs from new mines and facing increasing foreign competition (particularly from north Africa and the Middle East). Although the United Staes has sufficient phosphate rock resources to satisfy domestic consumption for many years to come, its ability to economically compete in the major export markets will face increasing challenges in the future.

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APPENDIX A.--PHOSPHORIC ACID PRODUCTION AND COSTS

Most of the phosphate rock produced in the United States and the rest of the world is used to manufacture fertilizer products (phosphoric acids) to be used by the agricultural industry. The various fertilizer products produced from phosphate rock are wet-process phosphoric acids, normal superphosphates, triple superphosphates, monoammonium phosphates, and diammonium phosphates. Direct application of ground phosphate rock is used in many regions of the world, i.e., phosphate rock is applied directly to acidic soils.

The quality of phosphate rock for acid production is affected by the contained amounts of such deleterious materials as magnesium (MgO), iron and aluminum (Fe_2O_3 plus Al_2O_3), calcium (CaO), chlorine, and others. These impurities can cause problems during the production of phosphoric acids and tend to decrease the profitability of these operations by increasing costs.

The magnesium oxide content is undesirable because highly viscous magnesium phosphate "sludges" can form during the production of phosphoric acids, which can lower the operation's productivity and increase the energy requirements. The magnesium will also precipitate fluorine in the reactor stage of the wet-acid process, which causes plugging of the gypsum filters (33).[1] As a rule of thumb a magnesium oxide content of approximately 1% or higher will cause these problems and is typically unacceptable to an acid plant. In the United States there presently are Government programs and industry research directed to solving this problem (appendix C).

The iron and aluminum oxide content is also highly undesirable because it too forms viscous sludges and makes the acids "sticky." These problems occur if the combined iron and aluminum content (also called the I + A content) is greater than 2.5% to 3% and often market penalties are added.

The calcium content of the rock can affect the sulfuric acid requirements of phosphoric acid production. If the CaO:P_2O_5 ratio is greater than 1.6, excessive sulfuric acid will be required for the acidulation process.

Chlorine can cause excessive corrosion in the phosphate rock processing equipment. A chlorine content greater than 0.2% is presently considered undesirable.

Other materials are also considered deleterious to the processing of phosphate rock to its many end uses. These include fluorine (because of air pollution regulations in the United States), organic matter (because greater than 4% to 5% CO_2 can cause foaming in acid production), and trace metals (which also can cause the precipitation of sludges in acids).

The phosphate rock feed for acid production is usually dried and ground, although wet phosphate rock has recently become acceptable to some plants, particularly in the United States. Calcination of phosphate rock is not usually necessary prior to acid production and can be a very costly step if required; however, calcined acid plant feed produces very high quality phosphoric acid (33).

The most common fertilizer product is phosphoric acid, produced by the wet-process method. The principal reaction involved in all wet-process phosphoric acid plants is the digestion by sulfuric acid of tricalcium phosphate, the primary constituent of phosphate ores. This results in the precipitation of gypsum and the formation of phosphoric acid in solution. Most phosphoric acid processes digest the phosphate rock with sulfuric acid; in Europe there are some processes that utilize nitric acid for this digestion (33).

[1]Underlined numbers in parentheses refer to items in the list of references preceding this appendix.

The basic process by which phosphoric acid is produced by the wet-process method is shown in figure A-1. Phosphate rock is fed continuously into a stirred reactor vessel containing a slurry of unattached phosphate rock, sulfuric acid, and gypsum crystals. The tricalcium phosphate in the ore is dissolved by the free sulfuric acid, forming phosphoric acid and calcium sulfate; a precipitate of gypsum as filterable crystal will subsequently form. The gypsum crystals, after being increased in size by recirculating the acid slurry in a series of reactors, are separated from the acid by a filtration process. The gypsum is then sent to waste disposal areas since there is presently no economic market for this product. The phosphoric acid at this time is weak, containing only 28% to 30% P_2O_5, with small quantities of sulfuric acid still present. The strength of the acid is increased by evaporating water from it. This is the stage where contaminants (particularly iron, aluminum, and magnesium oxides) can cause problems since they tend to start precipitating out of the acid as a "sludge," which is difficult to store, ship, or handle. In addition, these precipitated contaminants develop as complex phosphate compounds containing large amounts of P_2O_5, reducing the grade of the acid produced. The phosphoric acid will increase in quality through vacuum evaporation stages to approximately 30% to 45% P_2O_5. These are only nominal strengths, but thorough clarification (removal of much of the sludge) will result in typical merchant-grade phosphoric acid (approximately 54% P_2O_5) (33).

Merchant-grade acid is one of the most common products from a wet-process phosphoric acid plant. It has been more prevalent in recent years because it is low in impurities; therefore the acid can be shipped without large amounts of precipitated solids.

Typical production costs for phosphoric acid plants around the world, summarized by region, are shown in table A-1. These costs include processing phosphate rock

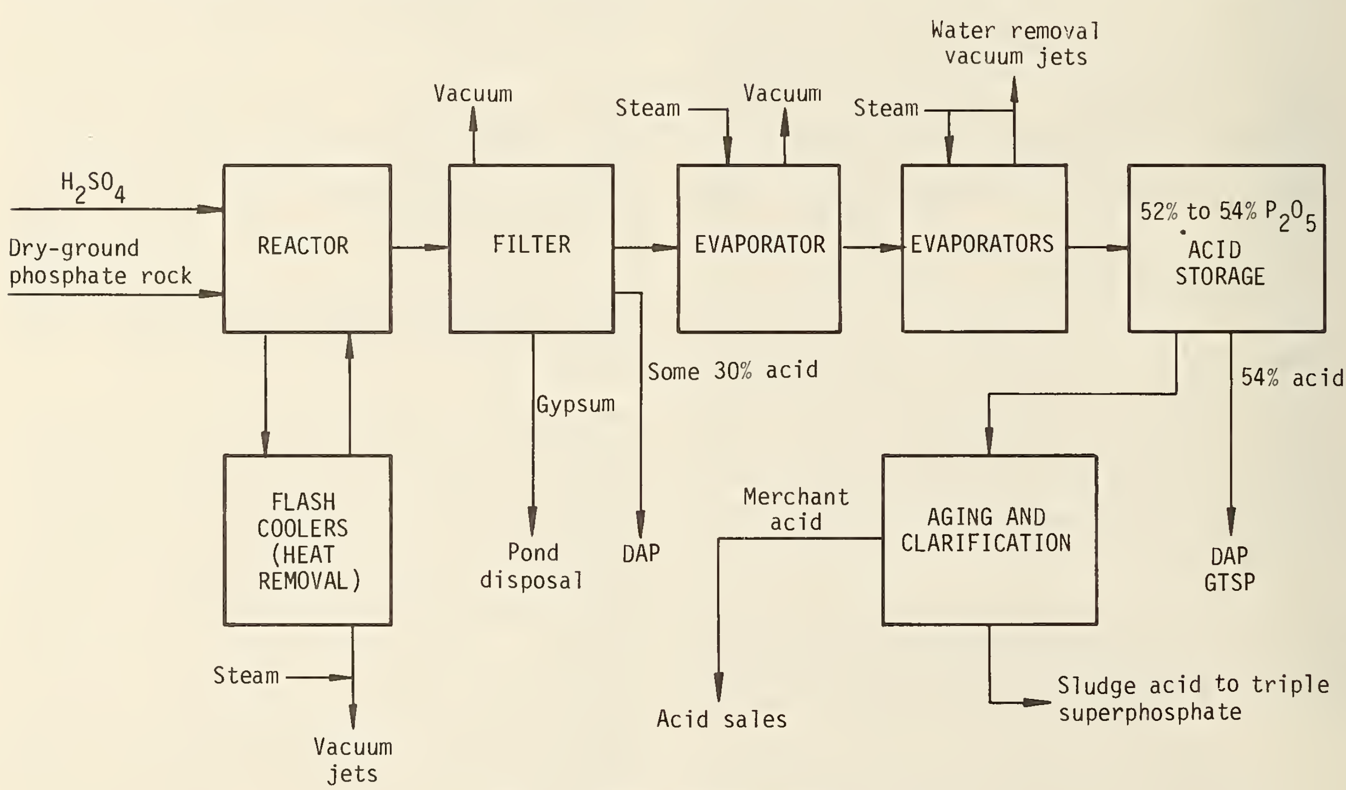

FIGURE A-1. - Wet-process phosphoric acid (1).

from a stockpile to merchant-grade acid in storage tanks, producing sulfuric acid from liquid sulfur delivered to the facility, and disposing of the byproduct gypsum.

TABLE A-1. - Phosphoric acid production costs, by region

Region	Cost[1]	Region	Cost[1]
North America	$192	Asia	$202
South America	203	Middle East	188
Western Europe	203	Africa	197

[1]Costs are in 1981 U.S. dollars per metric ton of P_2O_5.

Source: These costs were developed by Zellars-Williams, Inc., Lakeland, FL, under contract J0377000.

APPENDIX B.--WORLD PHOSPHATE DEPOSIT INFORMATION OF THOSE DEPOSITS INCLUDED IN THE STUDY

Country and deposit name	Owner	Status (1)	Mine method (2)	Mill method (3)	Deposit type (4)	Initial year of production (5)	Feed grade, wt % P_2O_5	Mill capac., 10^3 tpy[6]	Prod. grade, wt % P_2O_5	Prod. capac., 10^3 tpy[6]
United States:										
Florida:										
Acrefoot Johnson	Freeport Phosphate Mining Co	E	SL	F	SED	--	5.1	16,827	30.0	2,700
Big Four	AMAX Inc	P	SL	F	SED	1977	7.0	5,183	31.6	1,100
Bonny Lake	W. R. Grace Co	P	SL	F	SED	1958	9.6	10,585	32.5	2,900
Boyette and Fishawk	Agrico Chemical Co	E	SL	F	SED	--	7.4	3,758	33.9	700
Brooker-Dukes	Kerr-McGee Chemical Corp	E	SL	F	SED	--	6.5	13,870	31.6	2,700
C. F. Hardee Phosphate Complex	C. F. Industries Inc	P	SL	F	SED	1978	7.1	6,424	31.5	1,400
Christina	Mobil Chemical Co	E	SL	F	SED	--	8.0	2,062	33.4	500
Clear Springs	IMC Corp	P	SL	F	SED	1948	11.0	9,016	33.2	2,700
Cooks Hammock #1	Monsanto Co	E	SL	F	SED	--	4.3	4,198	33.0	500
Cooks Hammock #2	Unidentified major paper company	E	SL	F	SED	--	4.3	3,624	32.0	500
David C. Turner Heirs	Heirs of D. C. Turner	E	SL	F	SED	--	4.7	3,537	30.2	500
Deep Creek	Occidental Chemical Co	E	SL	F	SED	--	4.8	15,403	31.4	1,800
Deseret Ranch	Mormon Church	E	SL	F	SED	--	5.5	41,975	28.6	5,500
DeSoto-Manatee Reserve	AMAX Inc	D	SL	F	SED	--	6.1	18,104	30.7	3,400
Duette	ESTECH	D	SL	F	SED	--	5.6	15,951	31.1	2,700
Durranee-Waters Tract	U.S.S. Agri-Chemicals	E	SL	F	SED	--	6.8	5,055	31.1	900
Farmland Hardee	Farmland Industtries Inc	D	SL	F	SED	--	9.0	6,826	31.8	1,800
Farmland Hillsborough	...do	E	SL	F	SED	--	6.0	6,024	33.0	900
First Mississippi Chemical Tract	First Mississippi Chemical Corp	E	SL	F	SED	--	6.5	2,825	33.3	500
Fort Green	Agrico Chemical Co	P	SL	F	SED	1975	5.3	16,608	30.7	2,600
Fort Meade #1	Mobil Chemical Co	P	SL	F	SED	1945	8.6	12,994	33.0	3,200
Fort Meade #2	Gardinier Inc	P	SL	F	SED	1967	7.8	7,629	30.9	1,800
Four Corners	W. R. Grace Co	D	SL	F	SED	--	8.1	13,724	31.1	3,400
Fridovich	Agri-Lewis Corp	E	SL	F	SED	--	7.1	2,544	32.6	500
Hard Rock	T/A Minerals	E	SL	W	SED	--	7.6	431	34.3	100
Hard Rock-Colloidal Clay	Anco-Kellog-Howard-Loncala-Sun	P	SL	F	SED	1930	24.3	27	24.3	30
Hardee	First Mississippi Chemical Corp	E	SL	F	SED	--	5.2	17,849	30.7	2,700
Hardee West	Various ownerships	E	SL	F	SED	--	4.3	7,775	30.3	900
Hardrock	...do	E	SL	W	SED	--	8.0	2,263	34.3	500
Haynesworth	Brewster-American Cyanamid-Kerr-McGee	P	SL	F	SED	1965	9.6	10,585	32.5	3,000
Hillsborough Co.-Farmland/Brewster.	Praitt-Thompson-Jameson-Simms	E	SL	F	SED	--	5.7	3,227	33.3	500
Hookers Prairie	W. R. Grace Co	P	SL	F	SED	1976	8.8	9,636	31.5	2,500
Hopewell	American Cyanamid Co	D	SL	F	SED	1982	8.7	3,541	33.2	800
Hunt Brothers Ranch	IMC Corp	E	SL	F	SED	--	6.2	3,687	31.8	600
Keys	...do	E	SL	F	SED	--	4.0	24,930	29.6	2,300
Kingsford	...do	P	SL	F	SED	1965	8.2	16,279	31.6	4,000
La Crosse	Kerr-McGee Chemical Corp	E	SL	F	SED	--	6.2	2,792	31.6	500
Little Payne Creek	U.S.S. Agri-Chem-Gardinier-Others	E	SL	F	SED	--	9.7	9,308	31.1	2,700
Lonesome	Brewster Phosphates and American Cyanamid.	P	SL	F	SED	1976	10.5	8,505	33.9	2,500
Manatee North	W. R. Grace Co	E	SL	F	SED	--	5.6	17,666	29.9	2,700
Manatee South	...do	E	SL	F	SED	--	4.2	31,427	30.2	3,600
Manson-Jenkins	U.S.S. Agri-Chemicals	E	SL	F	SED	--	5.1	5,804	30.5	900
Mobil Area	Various ownerships	E	SL	F	SED	--	4.8	7,665	30.9	1,100
N.E. MAnatee Swift-Grace	W. R. Grace Co. and others	E	SL	F	SED	--	4.7	3,537	30.4	500
Nichols	Mobil Chemical Co	P	SL	F	SED	1970	8.9	4,855	31.8	1,300
No. Columbia County #2	South Resin Corp	E	SL	F	SED	--	3.9	17,447	28.4	1,800

Noralyn-Phosphoria	IMC Corp	P	SL	F	SED	1948	8.8	18,652	31.6	4,900
North Lake City	Kerr-McGee Chemical Corp	E	SL	F	SED	--	6.1	2,555	31.1	500
Northeast Manatee-Texaco	Various ownerships	E	SL	F	SED	--	3.8	8,833	30.7	900
Osceola National Forest	U.S. Forest Service	E	SL	F	SED	--	4.8	12,994	31.2	1,800
Payne Creek-Palmetto	Agrico Chemical Co	P	SL	F	SED	1966	7.8	12,337	31.1	2,700
Pierce-Pebbledale	...do	E	SL	F	SED	--	5.1	3,066	31.4	500
Pine Level	AMAX Inc	E	SL	F	SED	--	6.6	6,753	30.9	1,400
Polk County	T/A Minerals	P	SL	F	SED	1976	8.8	1,586	31.1	400
Rockland	U.S.S. Agri-Chemicals and Freeport Phosphate Co.	P	SL	F	SED	1968	8.0	7,921	31.1	1,800
Rutland-Colvin-Vale	IMC Corp	E	SL	F	SED	--	3.1	13,104	29.8	1,100
Saddle Creek-Ebersbach	Agrico Chemical Co	P	SL	F	SED	1950	7.2	5,001	32.9	900
Sarasota County No. 1	George Kelce	E	SL	F	SED	--	2.9	16,060	27.8	1,400
Silver City	ESTECH	P	SL	F	SED	1964	10.3	5,366	30.9	1,600
South Fort Meade	Mobil Chemical Co. and others	D	SL	F	SED	--	7.3	18,798	30.9	4,200
South Hardee	Gardinier Inc	E	SL	F	SED	--	5.6	15,075	30.7	2,300
Stanaland Ranch	IMC Corp	E	SL	F	SED	--	5.6	6,242	31.6	900
Sawannee River	Occidental Chemical Co	P	SL	F	SED	1965	5.8	17,849	32.4	2,500
Swift Creek	...do	P	SL	F	SED	1975	5.0	15,367	32.7	1,800
Swift-Durrance area	Various ownerships	E	SL	F	SED	--	5.0	3,468	31.2	500
Texaco Manatee	Texaco Inc	E	SL	F	SED	--	6.1	8,724	30.7	1,400
Waters Tract	U.S.S. Agri-Chemicals	E	SL	F	SED	--	5.0	6,497	30.2	900
Watson	ESTECH	P	SL	F	SED	1936	8.0	4,125	32.9	900
Wingate Creek	Beker Industries	D	SL	F	SED	1982	5.3	16,389	31.1	2,700
Zolfo Springs area small ownerships	Mining Development Corp	E	SL	F	SED	--	7.0	5,986	30.4	1,100
Zolfo-Stauffer	Stauffer Chemical Co	E	SL	F	SED	--	5.9	6,023	32.0	900
Idaho:										
Champ Lease-Mountain Fuel-Husky #1.	Beker Industries	D	OP	W	SED	--	25.8	2,496	33.0	1,500
Conda Mine & Smokey Canyon	J. R. Simplot Co	P	OP	C	SED	1920	24.0	1,785	33.0	1,000
Diamond Creek	Alumet Corp	E	OP	C	SED	--	25.0	1,451	33.0	800
Gay Mine-Dry Valley	J. R. Simplot Co. and FMC Corp	P	OP	C	SED	1946	25.0	1,800	27.0	1,600
Henry	Monsanto Co	P	OP	F	SED	1952	28.0	900	30.0	700
Maybe Canyon	Beker-Western Fertilizer	P	OP	W	SED	1966	26.0	2,503	33.0	1,500
N. Henry-Trail-Caldwell-Blackfoot	Monsanto Co	D	OP	F	SED	--	28.0	900	30.0	700
Wooley Valley-Rasmussen Ridge	Stauffer Chemical Co	P	OP	W	SED	1955	27.0	1,089	30.8	800
Montana: Warm Springs Creek	Cominco American Inc	P	R&P	S	SED	1929	31.0	159	31.0	200
North Carolina:										
Lee Creek	Texas Gulf Chemical Corp	P	SL	F	SED	1966	15.0	9,636	30.7	3,900
North Carolina Phosphate	North Carolina Phosphate Corp	D	SL	F	SED	--	16.0	9,636	30.7	4,100
Tennessee:										
Hickman and Maury Co. properties	M. C. West Inc	P	SL	W	SED	1938	20.1	635	26.0	300
Hooker Chemical properties	Hooker Chemical Co	P	SL	W	SED	1953	18.0	899	28.0	500
Monsanto properties	Monsanto Co	P	SL	W	SED	1938	20.5	1,814	26.0	1,100
Stauffer Chemical Co. property	Stauffer Chemical Co. and others	P	SL	W	SED	1896	20.1	635	26.0	300
Tennessee Valley Authority	Tennessee Valley Authority	PP	SL	W	SED	--	20.7	524	27.0	300
Utah:										
Central Wasatch Range #1	Public land, unleased	E	OP	F	SED	--	24.1	300	28.7	200
Central Wasatch Range #2	...do	E	OH	F	SED	--	20.1	1,250	28.8	700
Crawford Mountains #1	Stauffer Chemical Co	E	OP	F	SED	--	23.7	1,000	28.4	800
Crawford Mountains #2	...do	E	OP	F	SED	--	23.7	1,000	28.4	800
Crawford Mountains #3	...do	E	R&P	F	SED	--	19.5	250	26.0	100
Crawford Mountains #4	...do	E	R&P	F	SED	--	26.7	1,250	33.0	800
Crawford Mountains #5	...do	E	R&P	F	SED	--	20.5	250	28.7	100
Flaming Gorge #1	...do	E	OP	F	SED	--	23.1	1,000	29.0	700

See footnotes at end of table.

APPENDIX B.--WORLD PHOSPHATE DEPOSIT INFORMATION OF THOSE DEPOSITS INCLUDED IN THE STUDY--Continued

Country and deposit name	Owner	Status (1)	Mine method (2)	Mill method (3)	Deposit type (4)	Initial year of production (5)	Feed grade, wt % P_2O_5	Mill capac., 10^3 tpy[6]	Prod. grade, wt % P_2O_5	Prod. capac., 10^3 tpy[6]
United States--Con.										
Utah--Con.										
Flaming Gorge #2	Public land, unleased	E	R&P	F	SED	--	20.4	1,250	26.0	900
Flaming Gorge #3	...do	E	R&P	F	SED	--	19.4	250	26.0	200
Northern Wasatch Range	...do	E	OP	F	SED	--	26.3	1,000	32.4	700
Vernal	Chevron	P	OP	F	SED	1961	19.5	917	31.0	300
Vernal Field #1	U.S. Steel	E	OP	F	SED	--	20.6	1,000	26.0	700
Vernal Field #2	...do	E	OP	F	SED	--	20.8	1,000	26.0	720
Vernal Field #3	...do	E	R&P	C	SED	--	19.1	1,250	26.0	780
Vernal Field #4	...do	E	R&P	C	SED	--	16.9	2,500	26.0	1,301
Vernal Field #5	...do	E	R&P	C	SED	--	17.1	1,250	26.0	657
Wyoming:										
Gros Ventre Range #1	Public land, unleased	E	OP	F	SED	--	25.5	1,000	33.0	666
Gros Ventre Range #2	...do	E	OH	C	SED	--	20.9	5,000	26.4	3,521
Hoback Range #1	...do	E	OP	F	SED	--	21.5	1,000	28.0	668
Hoback Range #2	...do	E	OP	F	SED	--	20.9	1,000	26.0	724
Hoback Range #3	...do	E	OH	F	SED	--	19.6	1,250	26.0	752
S.E. Wind River Range #1	...do	E	OP	F	SED	--	20.2	1,000	26.0	700
S.E. Wind River Range #2	...do	E	R&P	C	SED	--	18.1	2,500	26.0	1,444
Salt River Range #1	...do	E	OP	F	SED	--	24.9	1,000	30.2	800
Salt River Range #2	...do	E	OH	F	SED	--	18.3	2,500	26.0	1,270
Salt River Range #3	...do	E	OH	F	SED	--	24.6	1,250	33.0	604
Snake River #1	...do	E	OP	F	SED	--	25.9	1,000	30.4	785
Snake River #2	...do	E	R&P	F	SED	--	22.3	5,000	29.2	2,946
Snake River #3	...do	E	OP	S	SED	--	24.5	1,000	30.7	701
Snake River #4	...do	E	R&P	F	SED	--	20.4	1,250	30.3	479
Snake River #5	...do	E	R&P	F	SED	--	24.3	250	33.0	116
South Ridges #1	...do	E	OP	F	SED	--	23.2	1,000	28.8	717
South Ridges #2	...do	E	OH	F	SED	--	19.6	1,250	29.0	500
South Ridges #3	...do	E	OH	F	SED	--	22.9	5,000	27.2	3,000
Sublette Range #1	...do	E	OP	F	SED	--	23.1	1,000	27.6	800
Sublette Range #2	...do	E	OH	F	SED	--	20.0	1,250	28.1	600
Tunp #1	...do	E	OP	F	SED	--	23.6	1,000	28.7	700
Tunp #2	...do	E	OP	F	SED	--	24.5	1,000	28.7	800
Tunp #3	...do	E	OH	F	SED	--	22.5	250	33.0	100
Tunp #4	...do	E	OH	F	SED	--	19.8	250	26.0	200
Wyoming Range #1	...do	E	OP	F	SED	--	26.4	1,000	32.2	700
Wyoming Range #2	...do	E	R&P	F	SED	--	21.3	5,000	27.8	3,000
Algeria: Djebel Onk	Algerian Government	P	SL	W	SED	1965	24.6	3,600	31.8	2,000
Angola: Lacunga River	Angolan Government (Fosfang)	E	SL	W	SED	--	19.4	500	34.0	200
Australia:										
Christmas Island #1	Australian & New Zealand Government	P	SL	S	SED	1965	34.4	2,026	36.0	1,400
Christmas Island #2	...do	D	SL	W	SED	--	33.0	655	36.0	300
D-Tree	IMC Development Corp	E	SL	F	SED	--	18.6	8,602	34.0	4,000
Duchess	Western Mining Corp	P	SL	W	SED	1975	19.3	294	33.4	300
Lady Annie-Lady Jane	...do	E	SL	F	SED	--	17.0	9,412	34.0	4,000
Northern Deposits	...do	E	SL	F	SED	--	15.1	7,947	34.0	3,000

Brazil:										
Anitapolis	ILM Ind. Luchsinger Madorin	D	OP	F	IGN	--	6.7	3,602	35.1	600
Araxa-Arafertil	Arafertil	P	OP	F	IGN	1977	14.0	3,060	36.0	500
Araxa-Camig	...do	P	OP	F	IGN	1976	14.0	867	26.3	200
Catalao-Fosfago	Fosfago de Coias, S.A.	P	OP	F	IGN	1980	10.0	2,800	38.0	500
Catalao-Goiasfertil	Goias Fertilizantes	P	OP	F	IGN	1976	8.9	4,374	38.0	700
Ipanema I & II	Serrana, S.A.	D	OP	F	IGN	--	7.0	4,100	38.0	500
Itataia	Nuclebras	E	OP	F	HYD	--	11.0	1,875	33.0	500
Jacupiranga	Serrana, S.A.	P	OP	F	IGN	1965	5.0	4,335	35.0	500
Olinda-Paulista-Igarassu	Lundgren Group	E	SL	F	SED	--	20.0	680	28.0	300
Patos de Minas	Fertilizantes Fosfatos, S.A.	P	OP	F	SED	1977	13.0	3,200	30.0	1,000
Tapira	Fosfertil, S.A.	P	OP	F	IGN	1979	8.1	8,300	36.0	1,000
Canada: Cargill	Continental Copper Mines-IMC	E	OP	F	IGN	--	20.0	1,900	39.0	700
Colombia: Pesca-Conejera-Sardinata	Colombian Government (Ecominas)	P	R&P	F	SED	1979	18.0	430	29.0	100
Egypt:										
Abu Tartur	Arab Republic of Egypt	D	LW	F	SED	--	25.6	3,600	31.0	1,500
Hamrawein	Misr Phosphates	P	R&P	C	SED	1978	25.0	1,200	33.0	600
Quseir	Red Sea Phosphate Co.	P	R&P	W	SED	1980	21.0	200	26.0	100
Sabaiya East	Abu Zaabel Fertilizer Chemical Co.	P	R&P	F	SED	1977	26.0	110	26.0	100
Sabaiya West	...do	P	SL	F	SED	1977	22.0	180	28.0	100
Safaga	Red Sea Phosphate Co.	P	R&P	S	SED	1979	26.0	160	29.0	100
Finland:										
Siilinjarvi	Kemira Oy (Government of Finland)	P	OP	F	IGN	1980	4.0	6,000	35.9	500
Sokli	Rautaruukki Oy	E	OP	F	IGN	--	18.0	1,200	38.0	500
India: Jhamarkotra	Rajasthan State Mines & Minerals, Ltd	P	OP	S	SED	1970	21.7	1,700	31.4	1,100
Iraq: Akashat	State Organization for Minerals	P	SL	C	SED	1981	21.0	3,400	31.8	1,700
Israel:										
Arad	Negev Phosphates Ltd	P	OP	W	SED	1970	27.0	1,725	32.6	1,000
Nahal Zin	...do	P	OP	W	SED	1978	26.8	3,200	32.0	2,000
Oron	...do	P	OP	W	SED	1965	23.5	1,040	34.3	500
Jordan:										
El Hasa-El Abiad	Jordan Phosphate Mining Co.	P	SL	W	SED	1970	29.8	9,400	33.7	5,800
Esh-Shidiyah	...do	E	SL	W	SED	--	25.4	7,514	33.4	4,000
Ruseifa	...do	P	SL	W	SED	1965	25.0	1,320	32.0	800
Mexico:										
San Juan de la Costa	Government of Mexico	P	OP	F	SED	1980	19.0	2,000	31.0	800
Santo Domingo	...do	D	DR	F	SED	--	4.5	11,200	30.0	1,200
Morocco:										
Ben Guerir	Government of Morocco	P	SL	W	SED	1981	27.5	9,500	30.2	5,500
Daoui Nord	...do	P	SL	W	SED	1965	28.0	1,650	34.5	1,000
Daoui-Recette 4	...do	P	SL	W	SED	1971	26.0	15,000	32.1	8,700
Khouribga Underground	...do	P	R&P	W	SED	1965	29.0	4,643	32.3	3,000
Meraa El Arech	...do	P	SL	S	SED	1965	25.0	4,800	32.1	2,500
Meskala District	...do	E	SL	W	SED	--	30.5	2,800	31.0	2,100
Sidi Hajjaj	...do	D	SL	W	SED	--	29.0	6,500	31.0	3,100
Southern Khouribga Region	...do	E	SL	W	SED	--	25.0	9,210	32.0	4,700
Youssoufia Black Rock	...do	P	LW	S	SED	1974	27.5	4,444	34.0	2,000
Youssoufia Open Cast	...do	P	SL	S	SED	1965	30.5	3,250	31.2	2,100
Youssoufia White Rock	...do	P	R&P	S	SED	1980	30.0	8,750	31.0	5,600
Nauru: Nauru	Nauru Phosphate Corp.	P	SL	S	SED	1965	38.4	3,600	39.4	2,500
Peru: Bayovar	Government of Peru	D	SL	W	SED	--	5.3	17,000	30.5	3,400
Saudi Arabia: West Thaniyat	Government of Saudi Arabia-Granges Intl.	E	LW	S	SED	--	22.0	5,000	35.0	2,500

See footnotes at end of table.

APPENDIX B.--WORLD PHOSPHATE DEPOSIT INFORMATION OF THOSE DEPOSITS INCLUDED IN THE STUDY--Continued

Country and deposit name	Owner	Status (1)	Mine method (2)	Mill method (3)	Deposit type (4)	Initial year of production (5)	Feed grade, wt % P_2O_5	Mill capac., 10^3 tpy[6]	Prod. grade, wt % P_2O_5	Prod. capac., 10^3 tpy[6]
Senegal:										
Pallo (Thies)	Senegal Government, Rhone-Poulenc	P	SL	S	SED	1965	28.0	420	30.0	300
Taiba	Senegal Government-BRGM-IMC	P	SL	F	SED	1965	31.0	6,400	33.5	1,500
South Africa: Palabora (Foskor Operation).	Foskor (Phosphate Development)	P	OP	F	IGN	1965	6.0	23,900	36.5	3,300
Syria:										
Kneifess	Gecopham (General Co. of Phosphate)	P	OP	S	SED	1971	28.0	1,050	32.0	600
Sharkya (A & B)	...do	P	OP	S	SED	1974	25.0	2,610	30.0	1,500
Togo: Hahotoe-Kpogame	Togo Government	P	SL	W	SED	1965	30.0	5,220	36.0	3,000
Tunisia:										
Kalaa Khasba	CIE Des Phosphates De Gafsa (Govt.)	P	R&P	W	SED	1980	27.5	340	30.2	200
Kef Eschfair	...do	P	SL	W	SED	1972	28.0	1,950	30.2	1,300
M'Dilla	...do	P	R&P	W	SED	1965	25.5	750	30.2	500
Metlaoui	...do	P	R&P	W	SED	1975	25.5	780	30.2	500
Moulares/M'Rata	...do	P	R&P	W	SED	1965	25.0	1,290	30.2	800
Redeyef	...do	P	R&P	S	SED	1965	25.0	1,200	28.0	800
Sehib	...do	P	LW	W	SED	1978	29.0	2,083	30.2	1,400
Turkey: Mardin-Mazidag	Etibank	T	SL	S	SED	—	18.0	280	28.5	100
Venezuela: Riecito	Petroquimica de Venezuela	P	OP	F	SED	1965	26.1	750	31.8	500
Western Sahara: Bou Craa	Governments of Morocco and Spain	T	SL	W	SED	—	32.0	5,000	36.6	3,000
Zimbabwe: Dorowa	African Explosive and Chemical Ind.	P	OP	F	IGN	1965	6.4	1,750	35.0	200
China:										
Gaiyang	Government of China	P	OH	S	SED	1964	33.0	2,000	35.0	1,600
Jingshan	...do	P	OH	S	SED	1965	26.5	400	28.0	300
Jinning	...do	P	OP	S	SED	1966	30.0	1,500	34.0	1,100
Kunming	...do	D	OP	F	SED	—	23.8	1,500	30.8	900
Shandong Province	...do	P	OH	S	IGN	1980	26.0	2,000	28.0	1,700
Zhongxiang	...do	P	OH	S	SED	1963	26.5	600	28.0	500
U.S.S.R.:										
Chilisay	Government of the U.S.S.R.	D	OP	F	SED	—	9.6	5,900	23.5	1,800
Kara Tau Deposits	...do	P	OP/OH	F	SED	1942	23.0	12,000	28.0	5,900
Kingisepp	...do	P	SL	F	SED	1963	6.2	8,400	28.5	1,400
Kirov	...do	P	OP/OH	F	IGN	1926	18.0	15,500	39.5	5,800
Koashva	...do	P	OH	F	IGN	1979	16.5	3,500	39.5	1,300
Kovdor	...do	P	OP	F	IGN	1974	12.5	3,400	35.0	900
Molodezhnyy	...do	P	OP/OH	F	IGN	1955	18.0	6,000	39.5	2,200
Oshurkov	...do	D	SL	F	HYD	—	4.7	9,300	35.0	800
Tsentralnyy	...do	P	OP	F	IGN	1964	16.5	23,000	39.5	8,600
Viatka-Kama	...do	P	SL	F	SED	1920	13.0	500	28.0	200
Yukspor	...do	P	OP	F	IGN	1955	18.0	5,500	39.5	2,000

[1] P Producer, D Developing, E Explored, PP Past producer, T Temporary shutdown.
[2] SL Strip level, OP Open pit, R&P Room and pillar, DR Dredge, OH Overhand stope, LW Longwall.
[3] F Flotation, W Wash, C Calcination, S Size.
[4] SED Sedimentary, IGN Igneous, HYD Hydrothermal.
[5] Dash indicates no production as of 1983.
[6] Actual or assumed estimated capacities in tons and metric tons per year.

APPENDIX C.--PRESENT RESEARCH IN PHOSPHATE

The following sections highlight the present research activity in phosphate in both the industry and the Bureau of Mines. Not all research will be discussed, just the most significant in terms of the future potential for improved phosphate recovery. These new processes, if successful, would increase the world phosphate resource potential.

RECOVERY OF PHOSPHATE ROCK FROM DEPOSITS CONTAINING HIGH MAGNESIUM

As previously discussed, the majority of phosphate rock produced in the United States is used for the manufacture of wet-process phosphoric acid, particularly in Florida and North Carolina. Increased amounts of magnesium oxide in the phosphate rock feed increase the viscosity of the acid, causing problems in producing standard diammonium phosphate. Traditionally phosphate rock over the years, especially from central Florida, has contained highly acceptable limits of MgO (lower than 0.5%). Much of the future phosphate resource potential from Florida (the southern extension) occurs in deposits containing presently unacceptable limits of magnesium oxide (greater than 1%). Presently, research work is underway to solve this problem by developing a method or methods to beneficiate high-magnesium phosphate to lower the MgO content to within the acceptable limit (1% or less). The Bureau of Mines Research Center in Tuscaloosa, AL, is presently working on this problem and has recently published a report dealing with this issue (35). Numerous phosphate companies in Florida are also working towards solving this problem.

BOREHOLE (SLURRY) MINING OF PHOSPHATE ORE

Presently, the Bureau of Mines is conducting research out of its Twin Cities, MN, center, in conjunction with a Florida phosphate producer, to develop a method to mine deep untapped phosphate resources in the southeastern United States (particularly in northeastern Florida). This method, called borehole mining, is a process in which deep phosphate ore is mined from the surface through a borehole using a water-jet cutting system to slurrify the ore, which is then pumped up to the surface.

BENEFICIATION OF LOW-GRADE WESTERN PHOSPHATES

Recent Bureau of Mines research at the Albany, OR, center has been dealing with methods to economically recover low-grade western phosphate resources. Flotation procedures have been studied, particularly a silica-carbonate flotation technique now in a pilot plant stage with industry. Other work by the Bureau and certain companies consists of methods to beneficiate unaltered phosphate resources and the feasibility of utilizing low-grade phosphatic shales as direct acid feed.

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